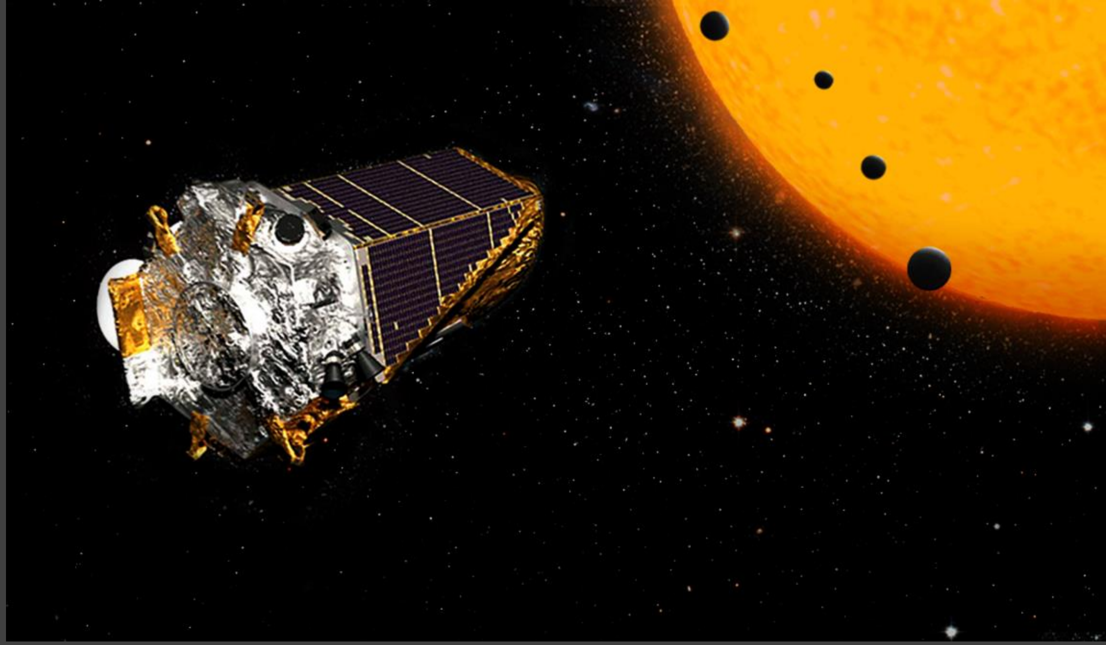
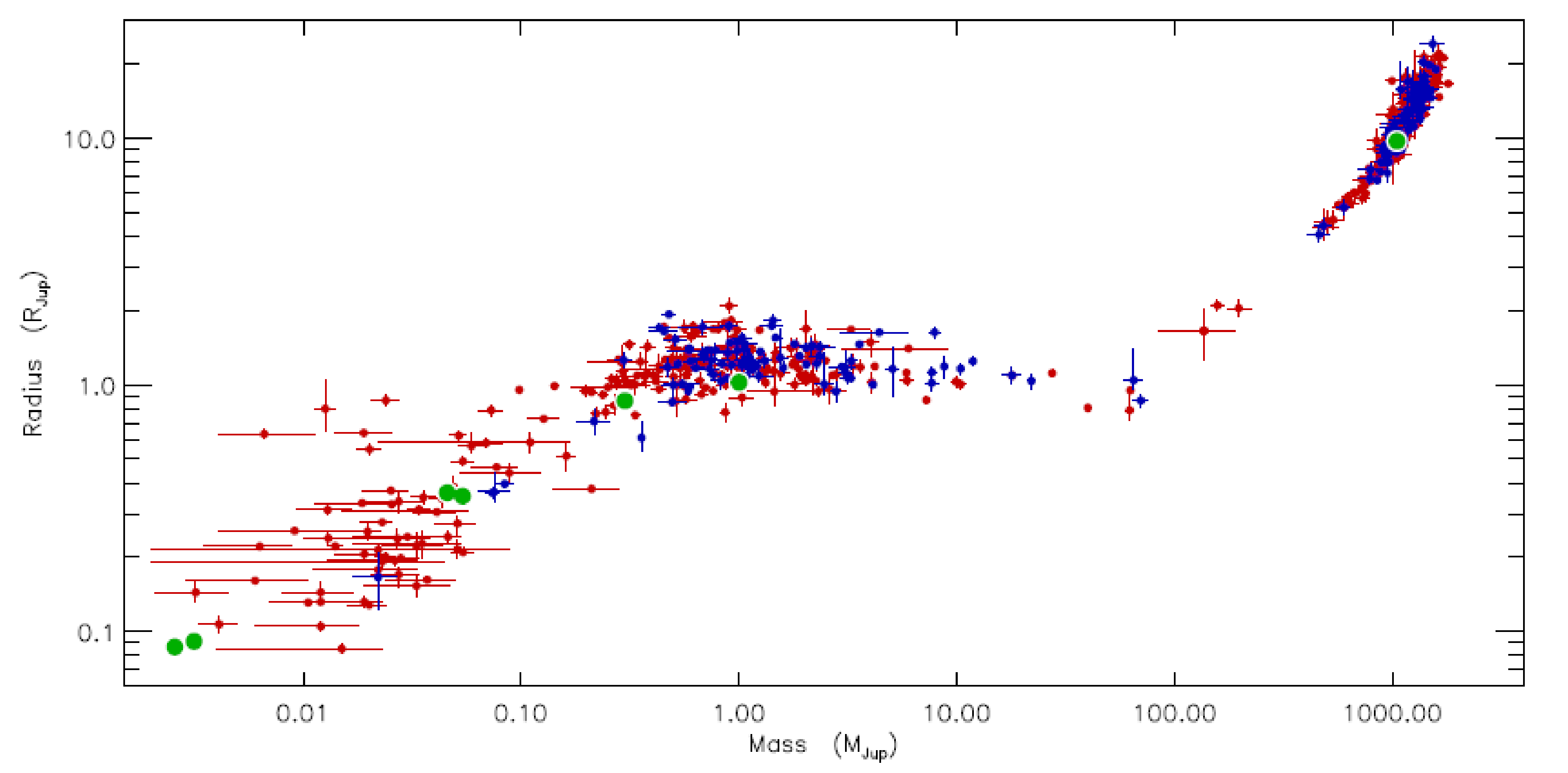


Planet detection methods

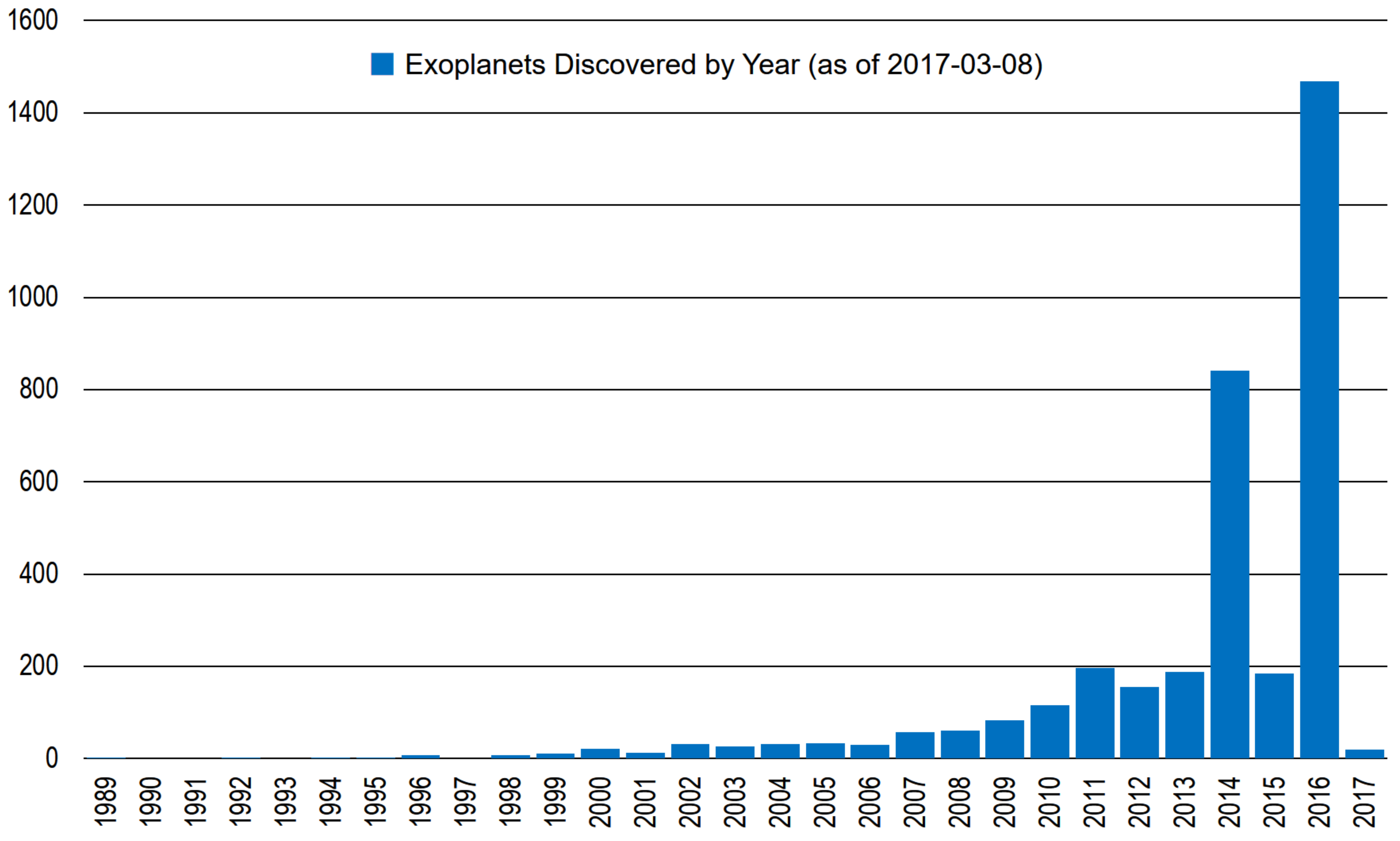
SERGEI POPOV

Planets, brown dwarfs stars



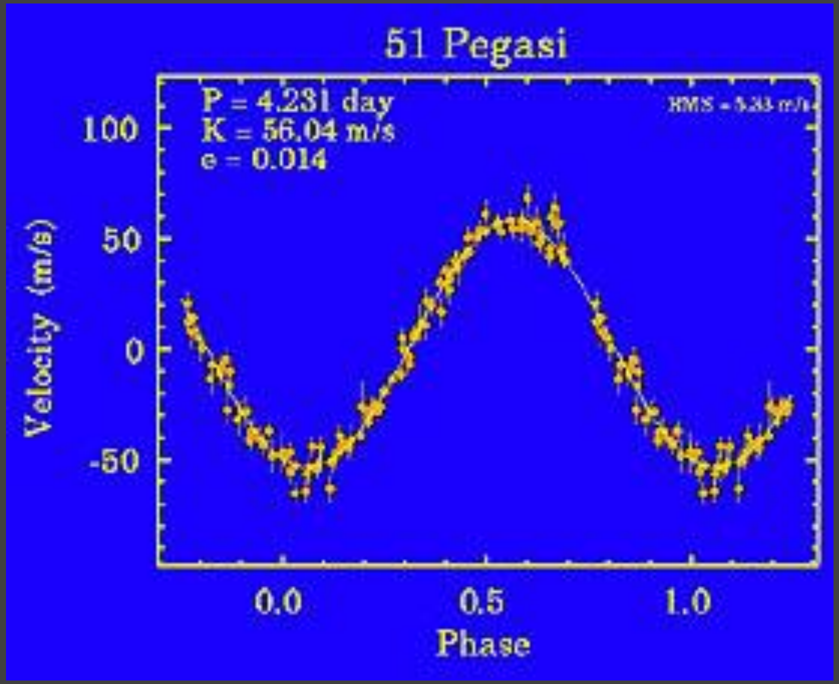
Brown dwarfs:
(12-13)<M<(75-80)
Jupiter masses

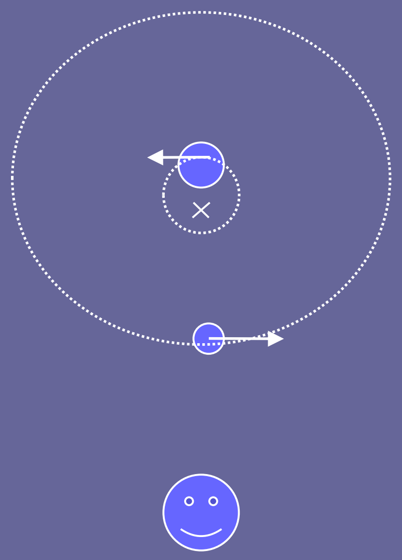
1411.5517


Exoplanets Discovered by Year (as of 2017-03-08)
1600
1400
1200
1000
800
600
400
200
0
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

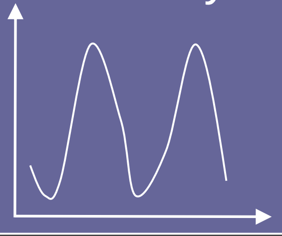
Radial velocities

Michel Mayor and Didier Queloz 1995



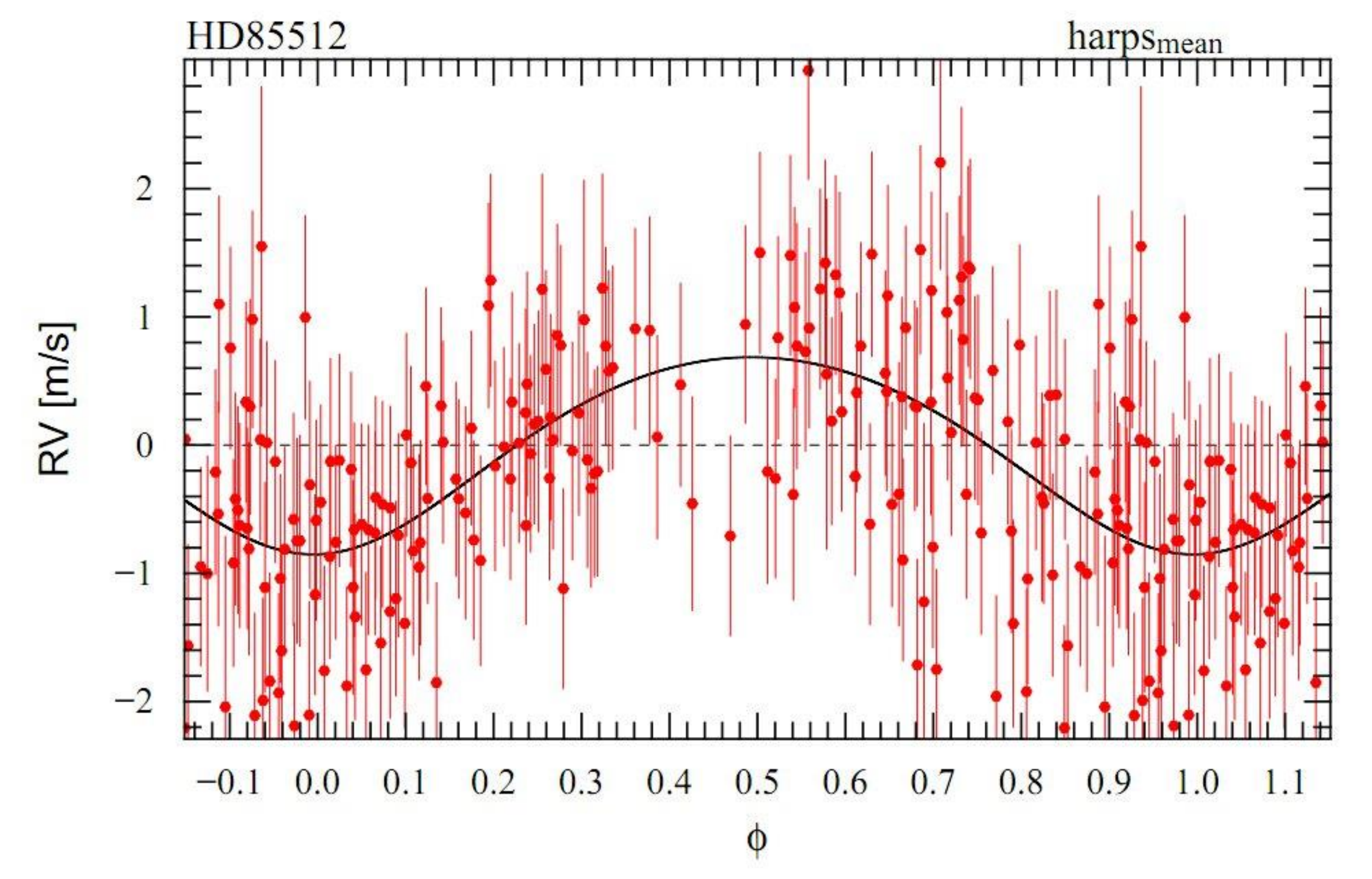


We see just the bright star.
We measure that its radial velocity periodically changes.



Measure:
- Period
- Mass

First light planets

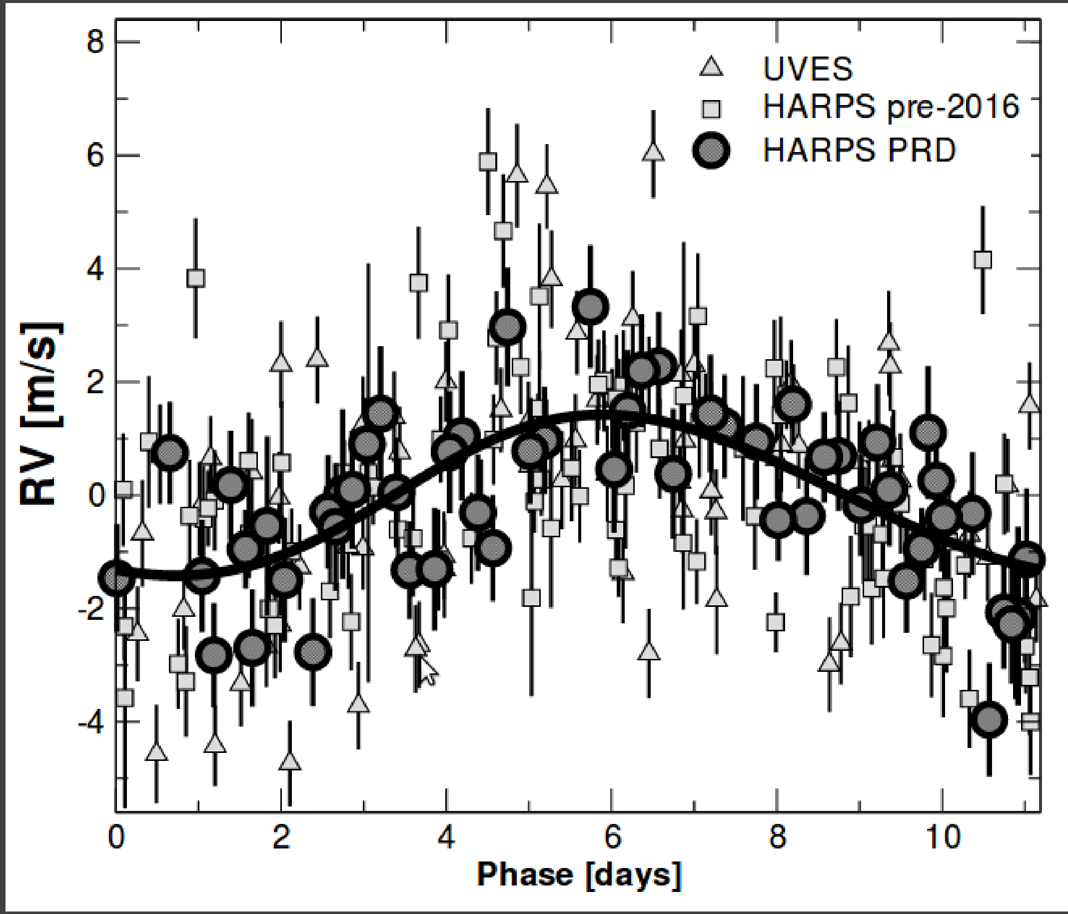


The problem is to measure
small velocity variations
for relatively long time.

Quality and stability of
the spectrograph is
more important than the telescope size.

This planet discovered by HARPS.
Situated just near the
zone of habilability.

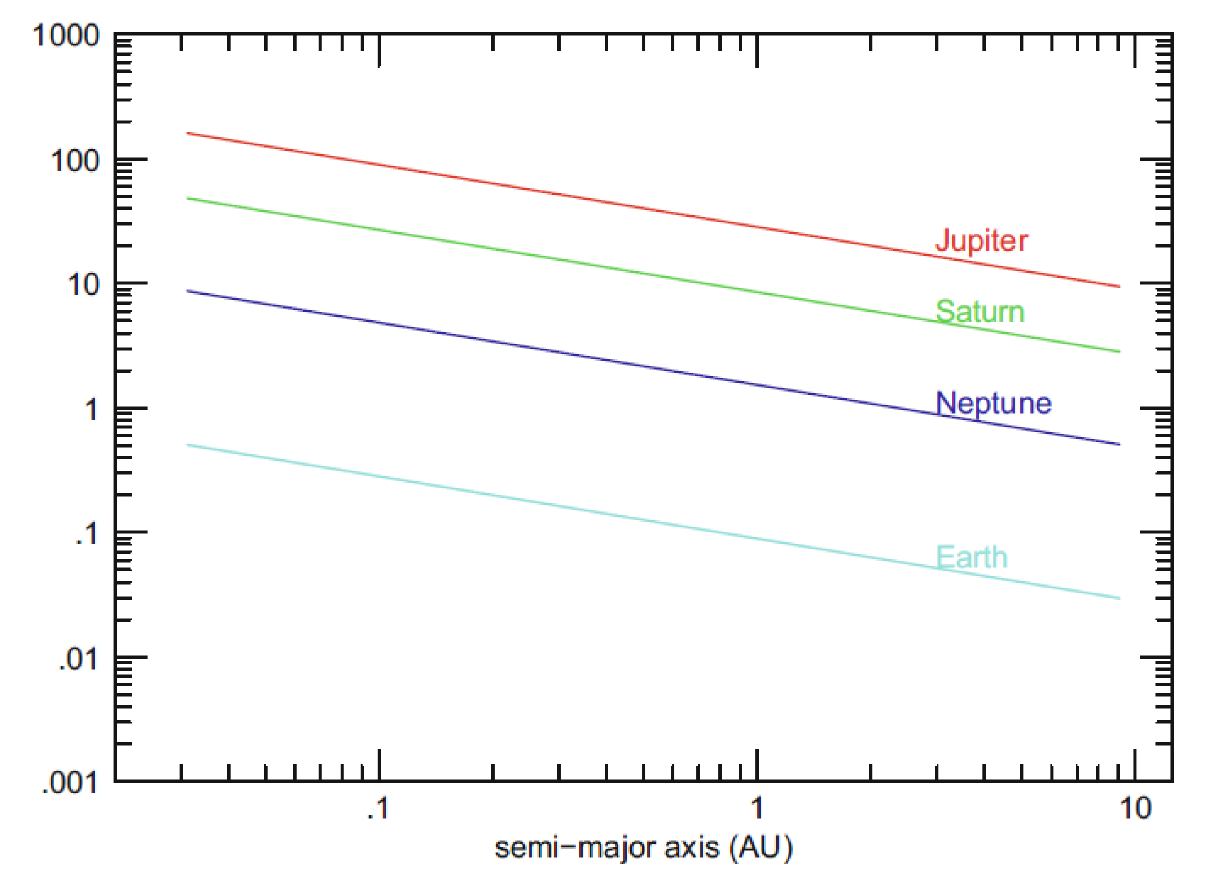
Proxima Centairu b

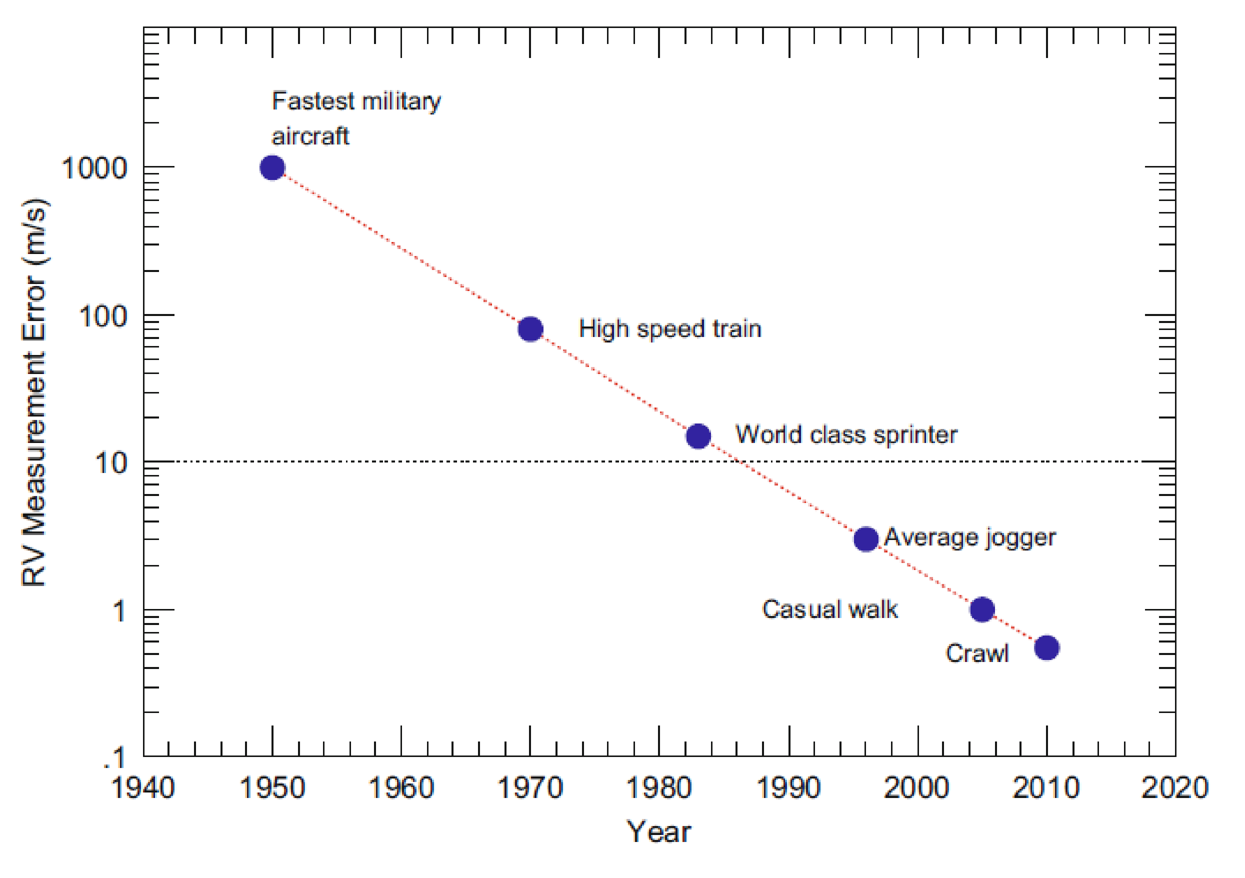


1.3 Earth masses
0.05 AU
11 days

Habitability zone

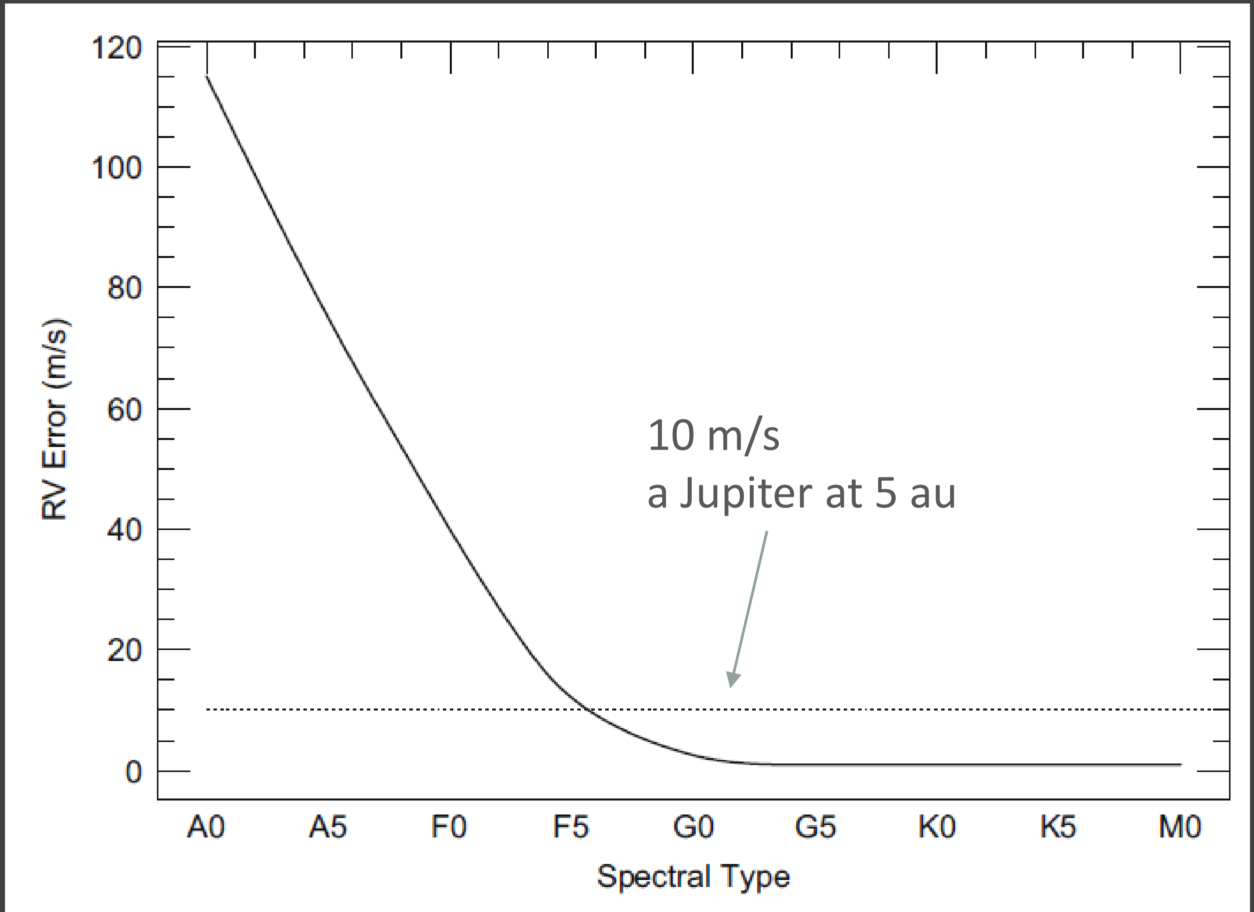
Radial velocities: data and measurements





Artie Hatzes (in Bozza et al. 2016)

Role of a star



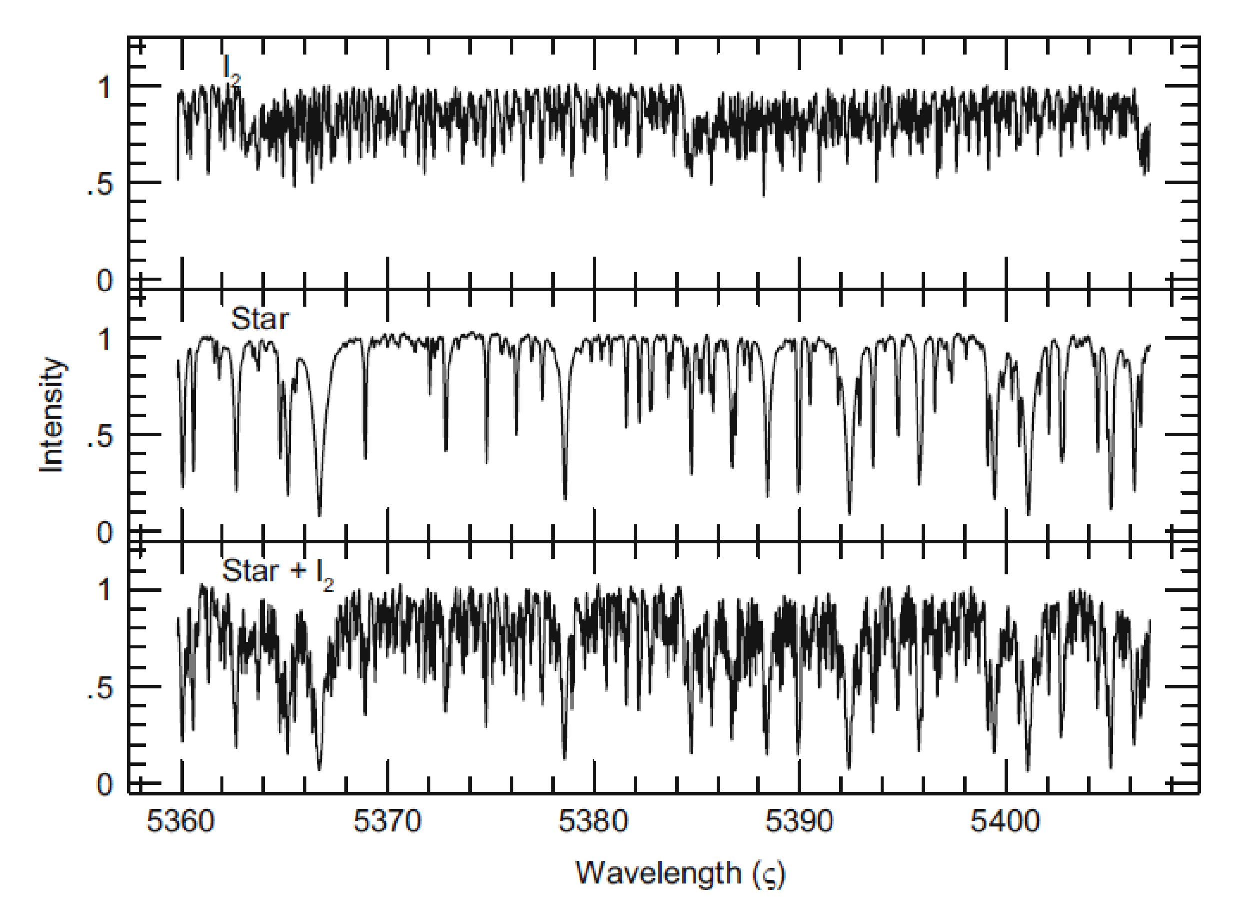
Difference is manly due to

- Rapid rotation
- Smaller number of spectral lines

Without additional errors due to the instrument:

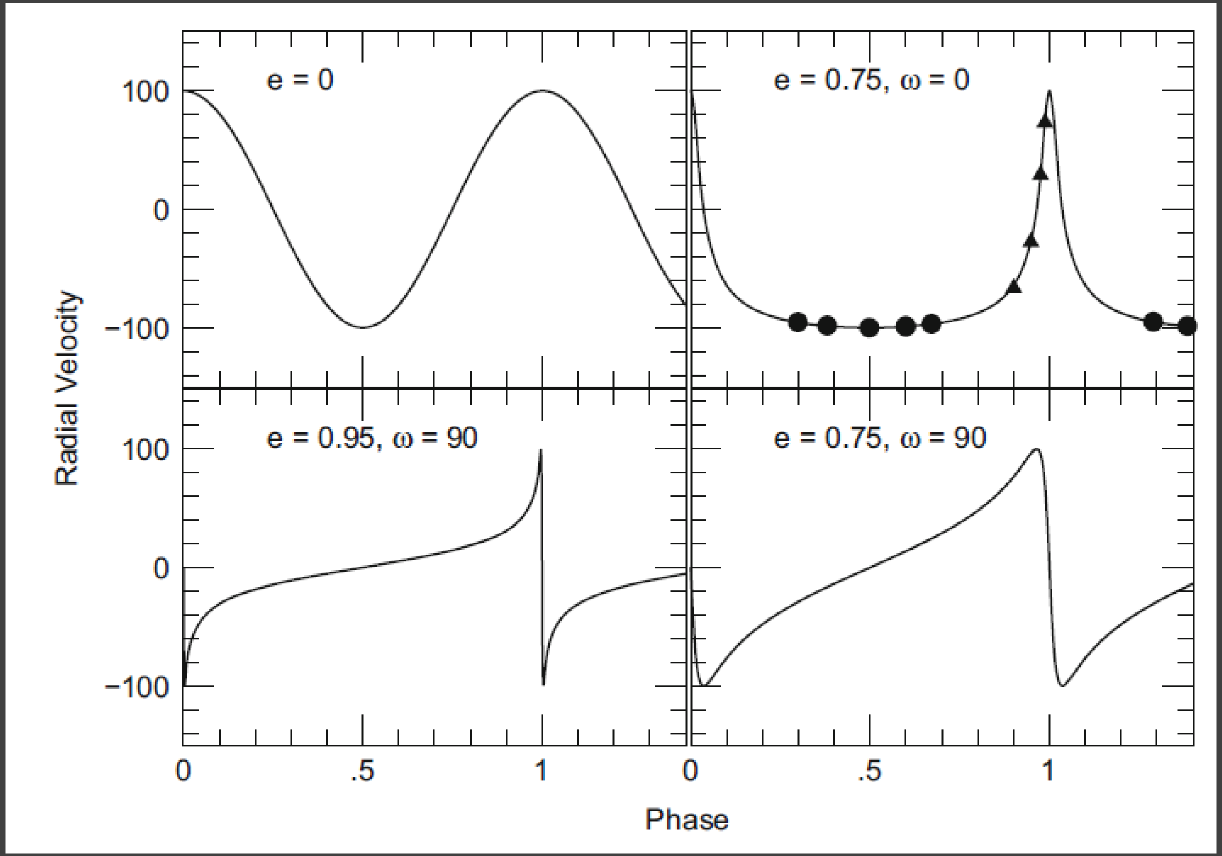
$$\sigma\,[\mathrm{m/s}] = C(\mathrm{S/N})^{-1}R^{-3/2}B^{-1/2}(v\sin i/2)f(\mathrm{SpT})$$

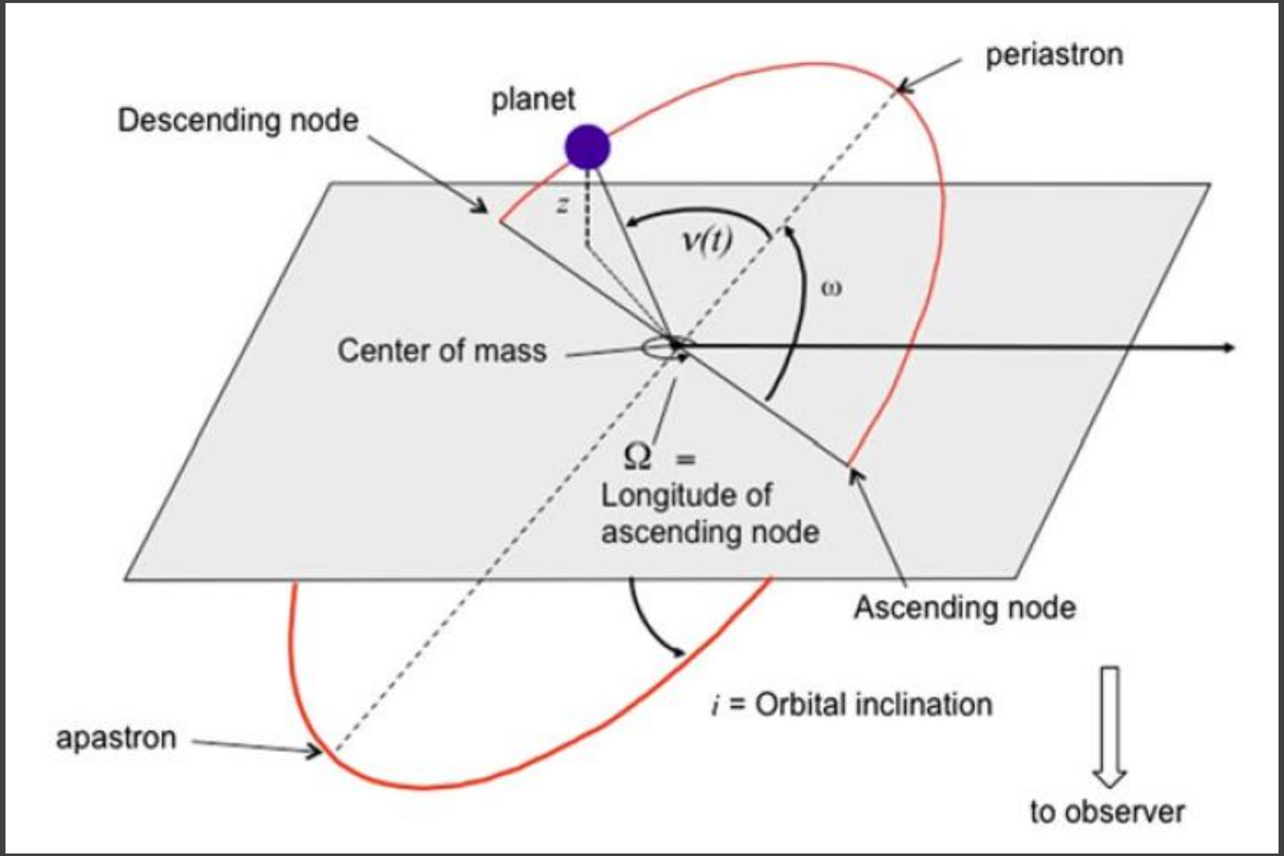
Molecular iodine cell



I_2 cell became the first effective tool to provide lines for RV measurements.

Velocity vs. phase for different orbits





Artie Hatzes (in Bozza et al. 2016)

Planet mass

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{K_1^3 P (1 - e^2)^{3/2}}{2\pi G} \approx \frac{M_2^3 \sin^3 i}{{M_1}^2}$$

Thus, it is necessary to know the stellar mass (M_1)

$$\langle \sin\, i \rangle = \frac{\int_0^\pi p(i) \sin\, i\, di}{\int_0^\pi p(i)\, di} = \frac{\pi}{4} = 0.79$$

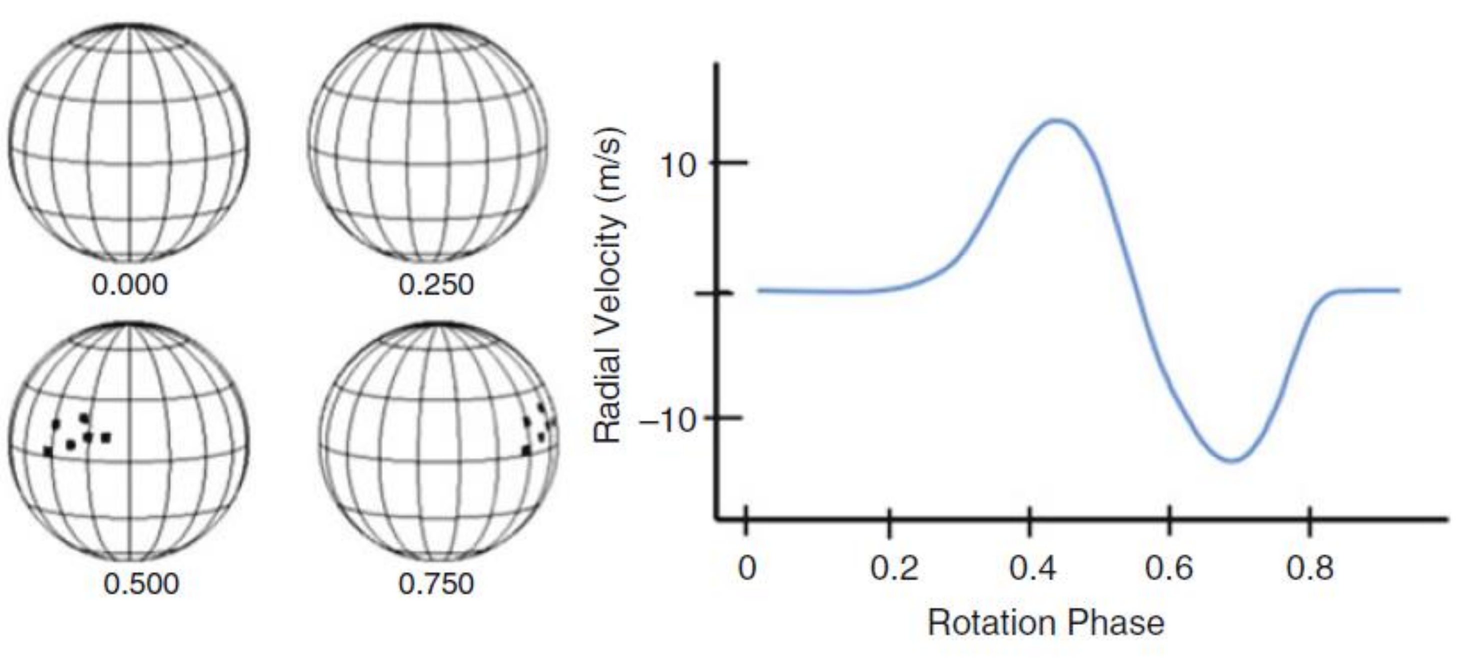
For the mass function
<$\sin^3$ i> is important:

$$\frac{\int_0^\pi p(i) \sin^3 i\, di}{\int_0^\pi p(i)\, di} = 0.5 \int_0^\pi \sin^4 i\, di = \frac{3\pi}{16} = 0.59$$

Artie Hatzes (in Bozza et al. 2016)

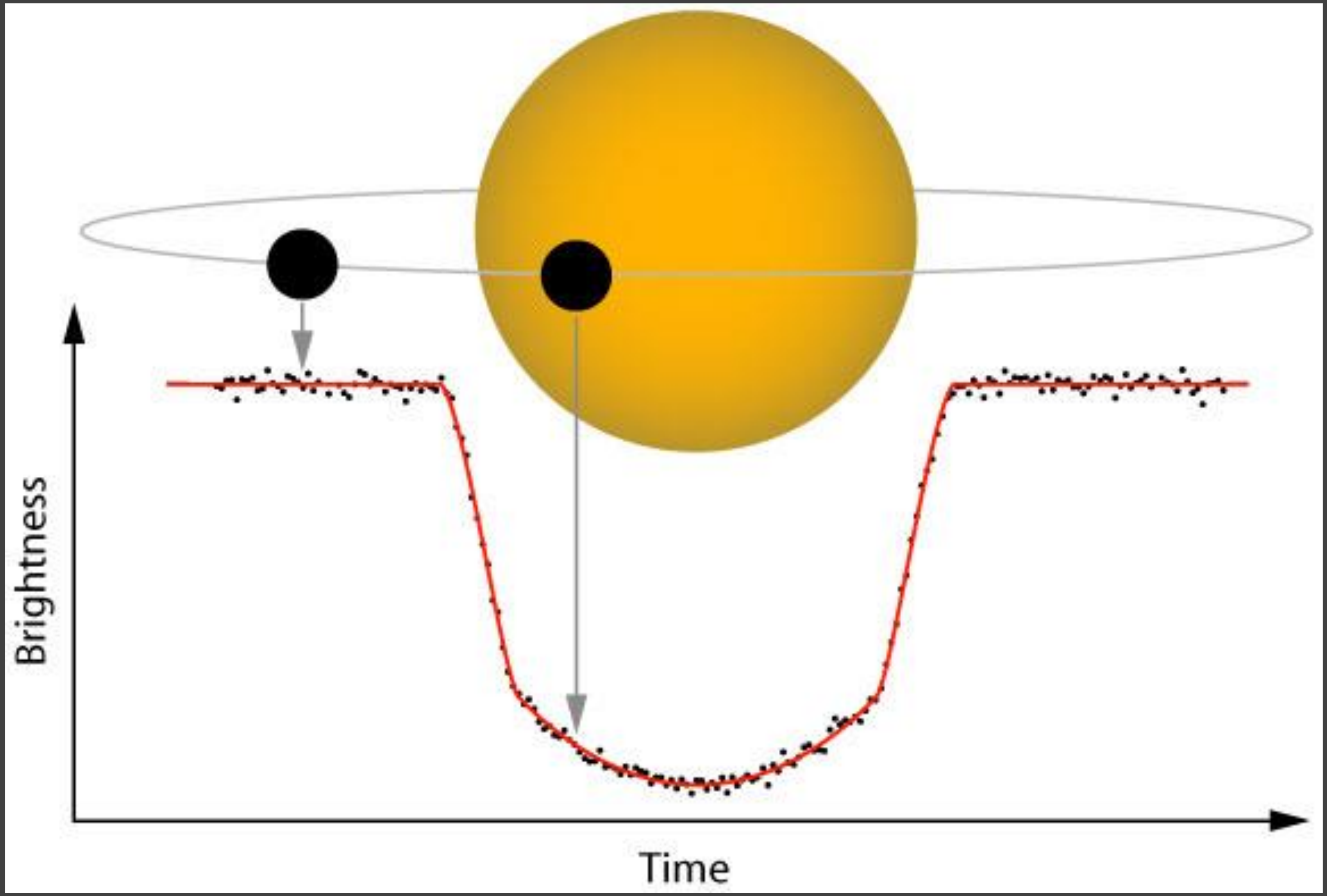
Stellar noise

Phenomenon	RV amplitude ($m\,s^{-1}$)	Time scales
Solar-like oscillations	0.2–0.5	~5–15 min
Stellar activity (e.g., spots)	1–200	~2–50 days
Granulation/Convection pattern	~ few	~3–30 years



Planet transits

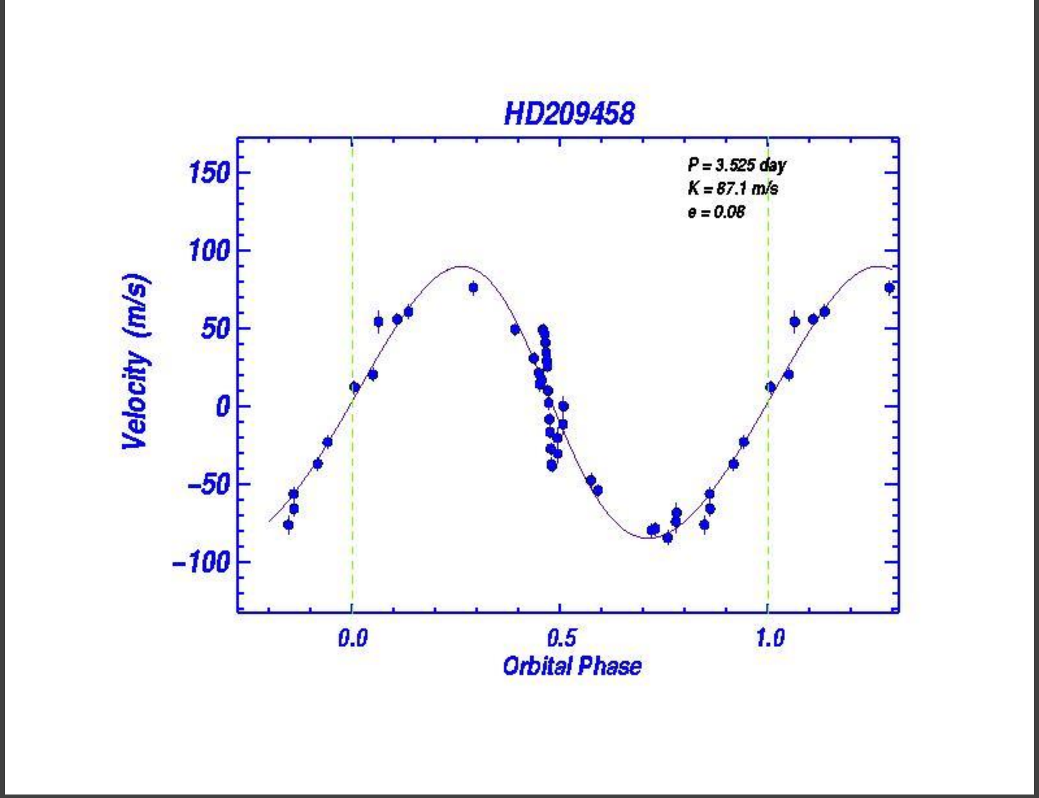
Proposed by
Otto Struve
in 1952

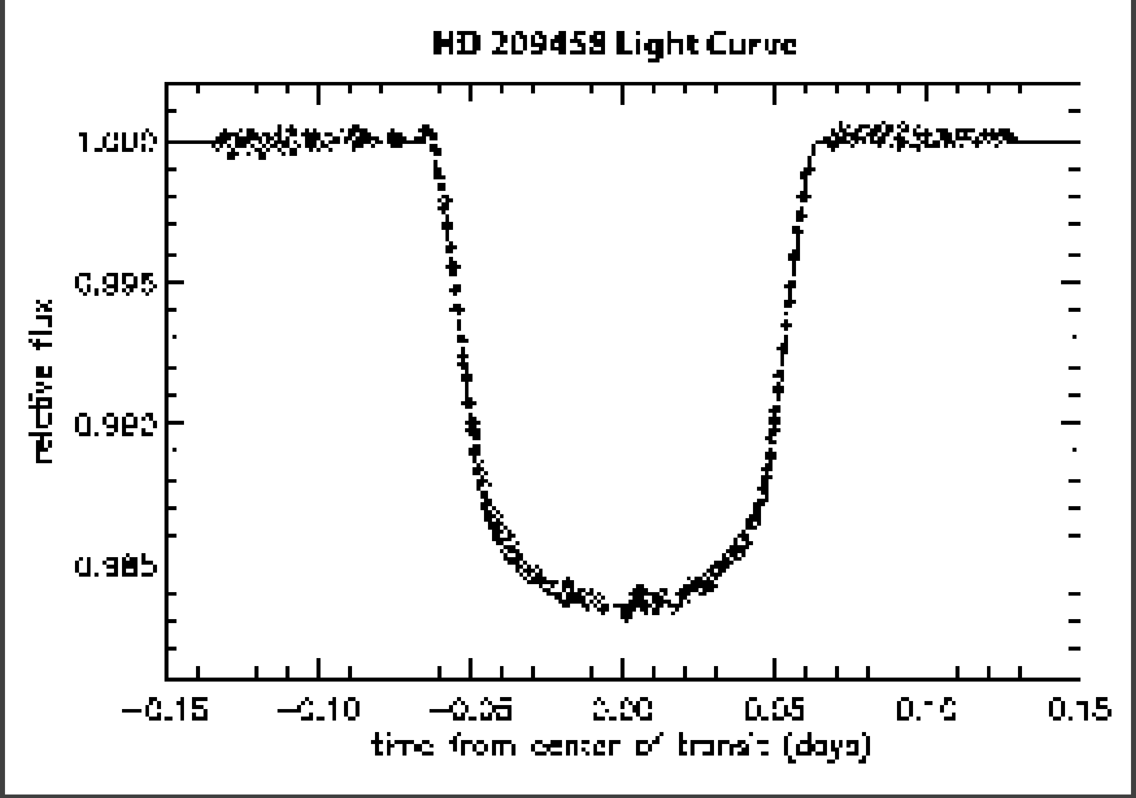


$$\frac{S_{star} - S_{planet}}{S_{star}}$$

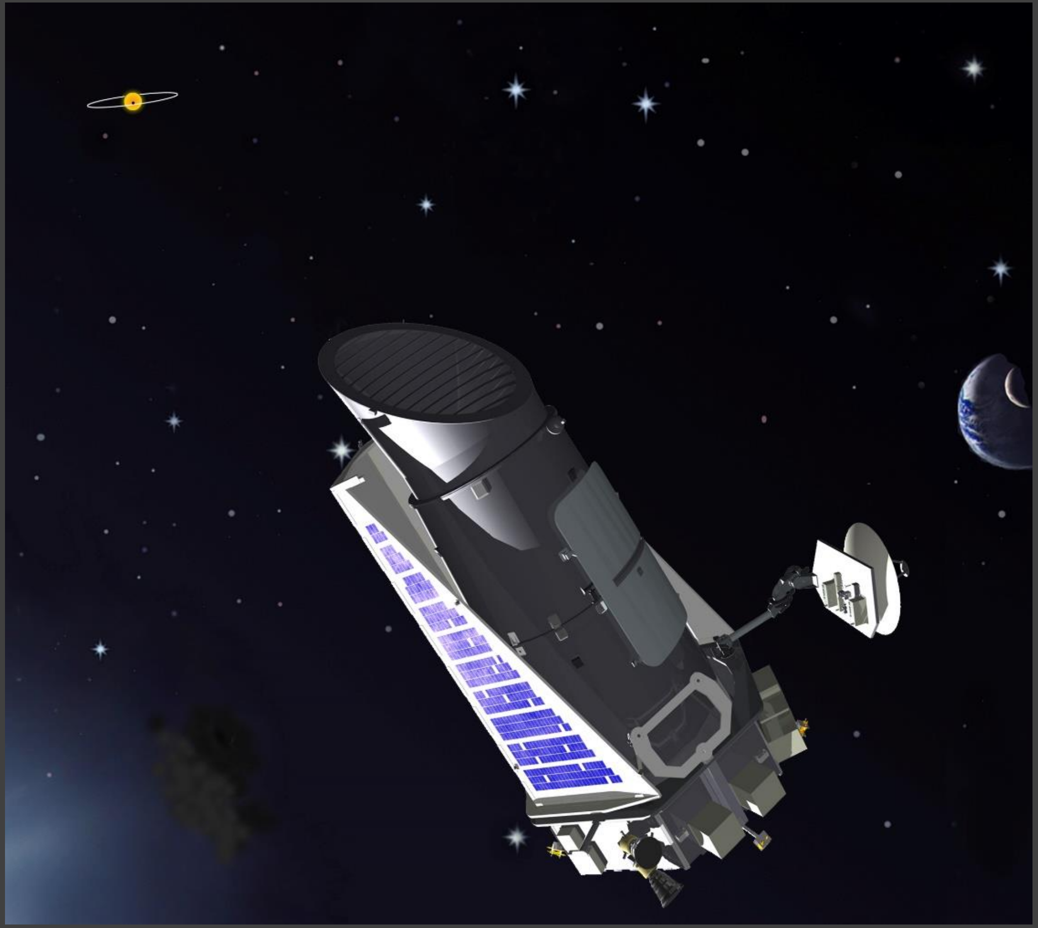
The first transit measurement. HD 209458

The first measurements of a transit was made from the ground
for a planet discovered by RV, and so known orbital parameters.

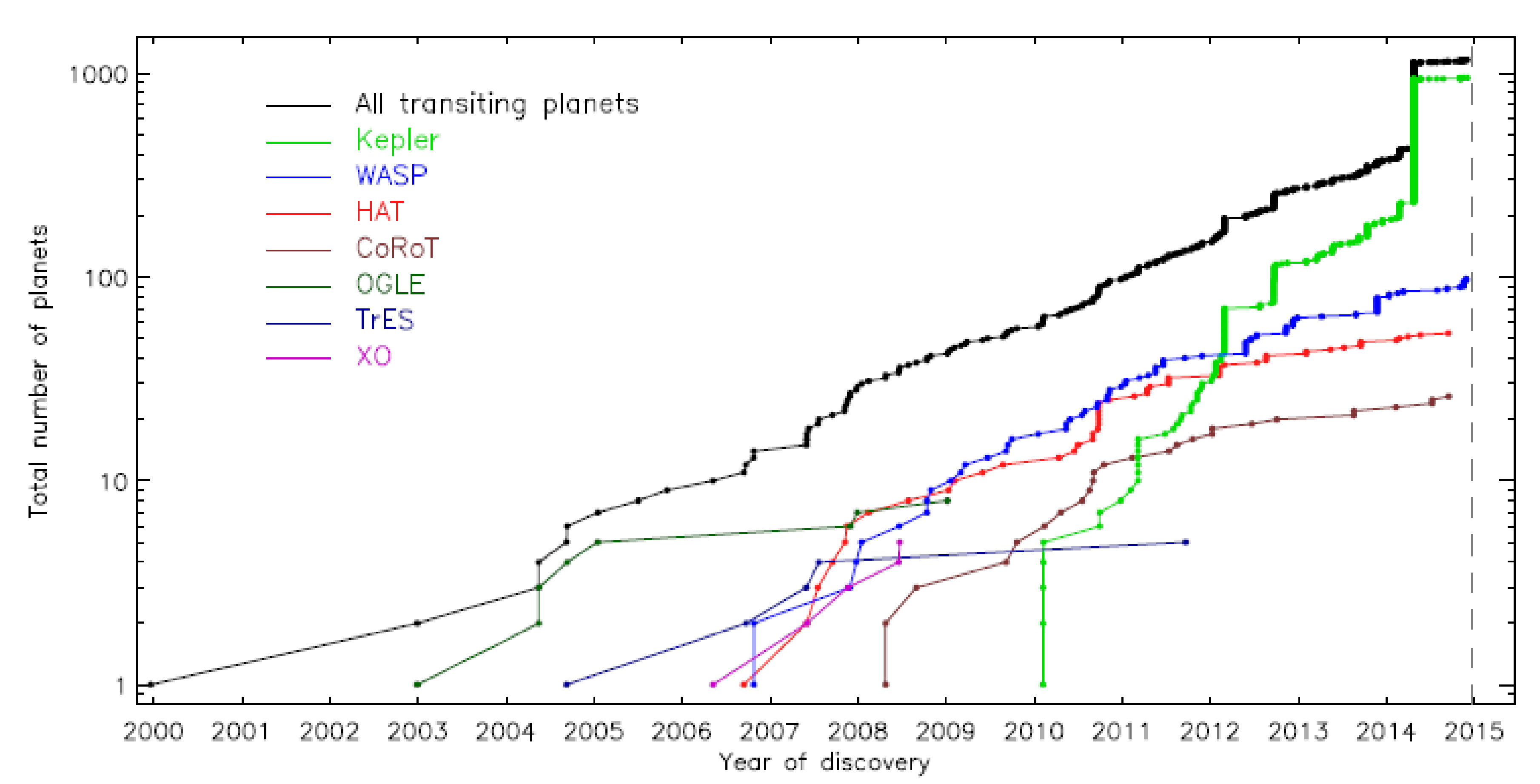




Kepler and CoRoT

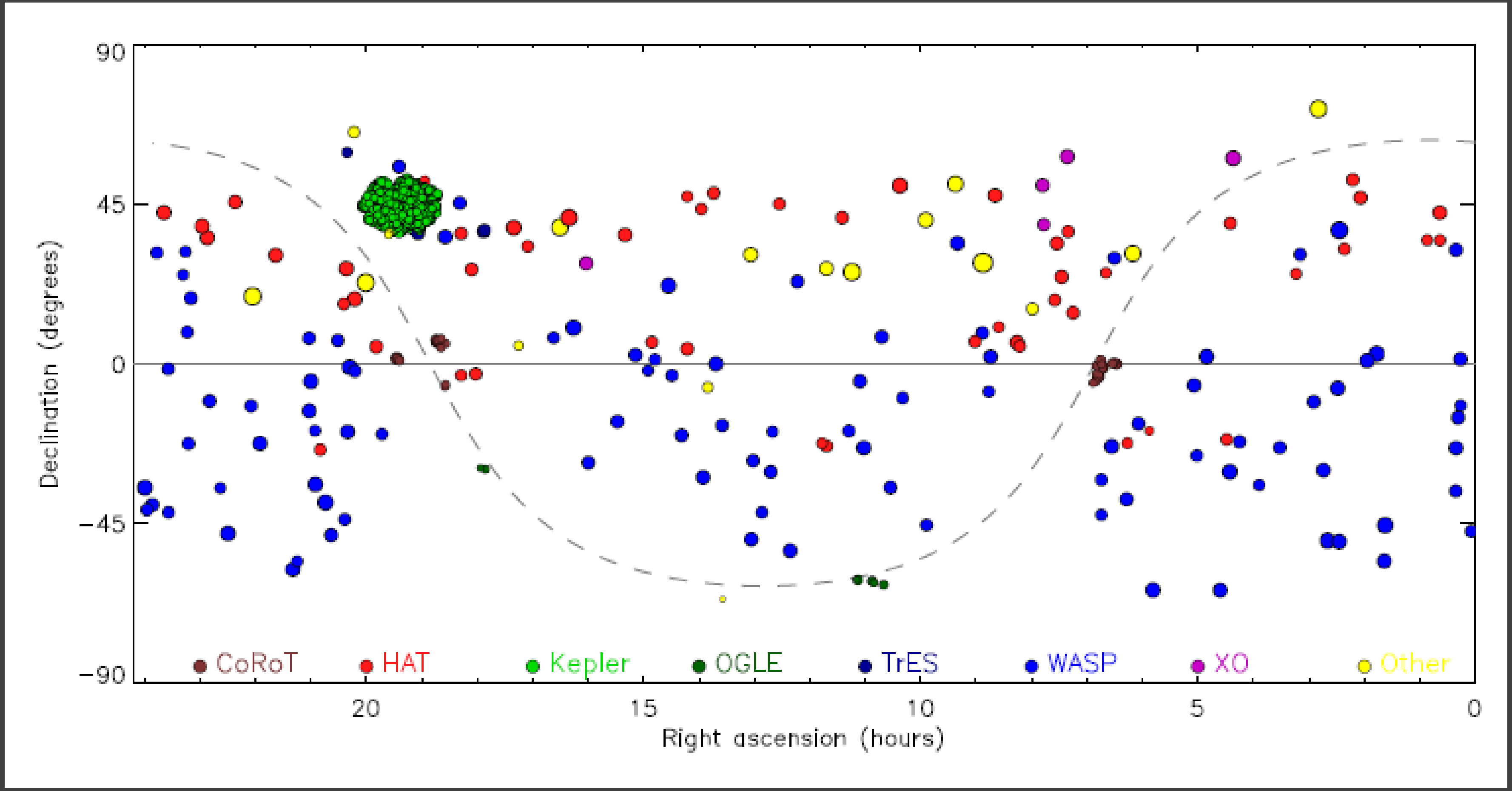


Rate of discovery



1411.5517

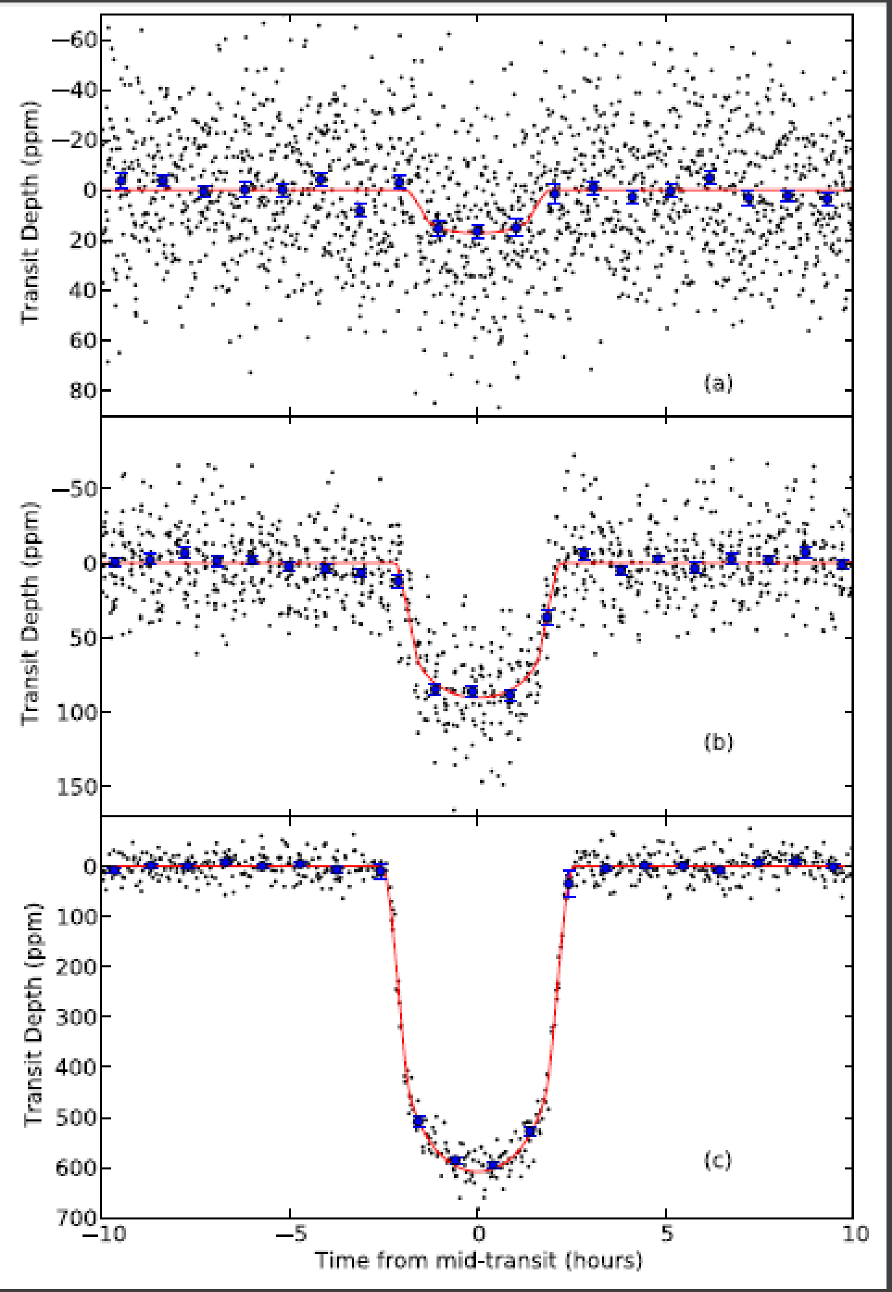
Transiting planets in the sky



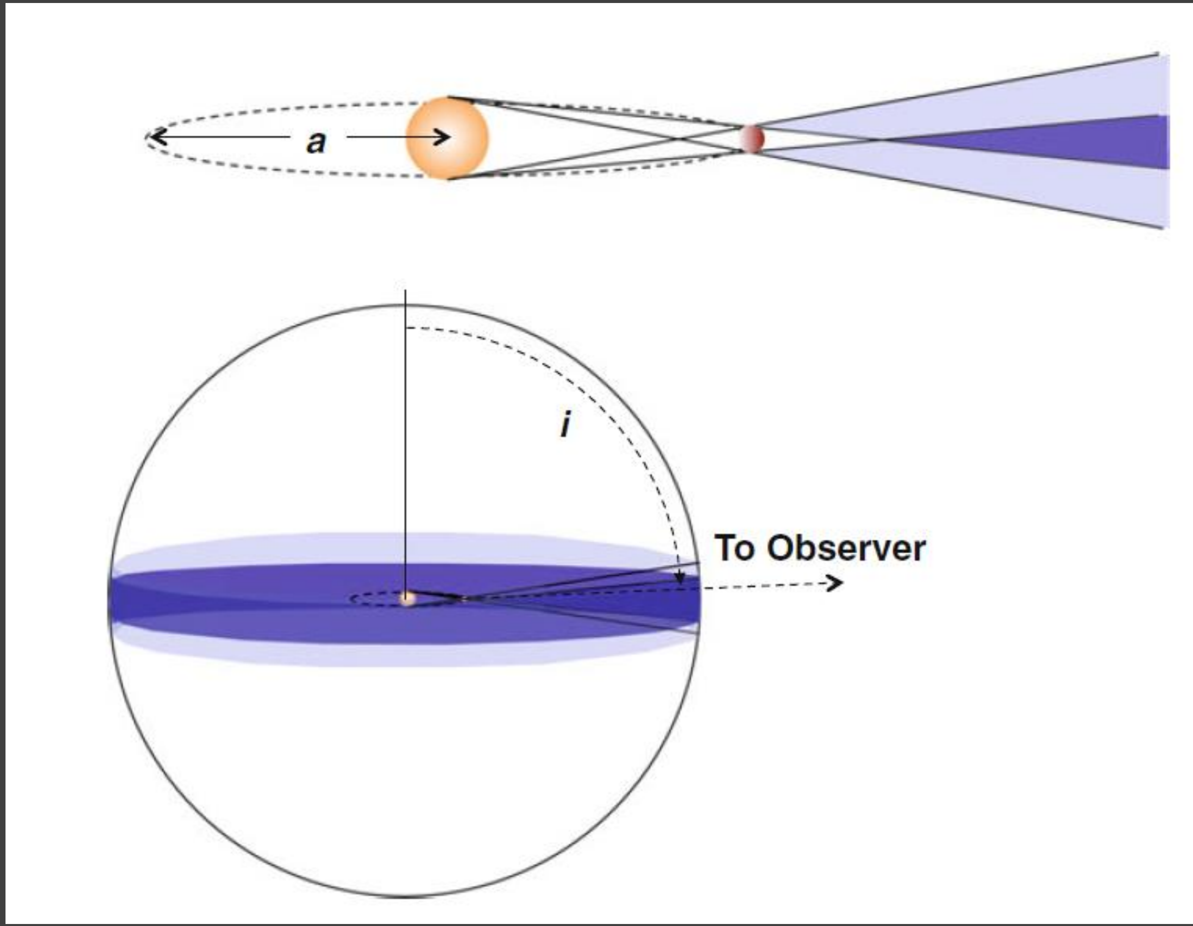
1411.5517

Very small planets

Kepler-37b
The first discovered exoplanet
with size smaller than Mercury



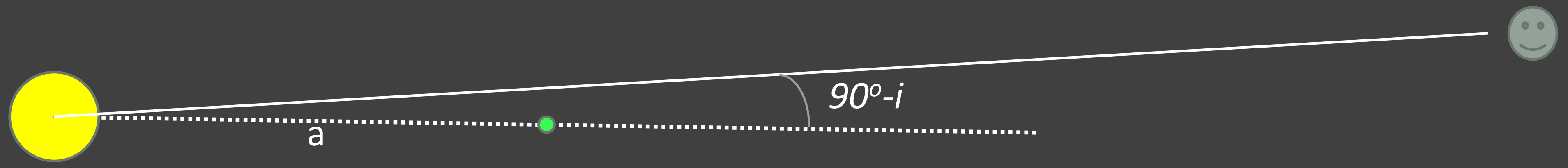
Transit probability



$$\Pr\left(\cos i < \frac{R_*}{a}\right) =\simeq 0.0046 \left(\frac{R_*}{R_\odot}\right)\left(\frac{1\,\mathrm{au}}{a}\right).$$

Andrew Cameron (in Bozza et al. 2016)

Transit conditions



$$b = \frac{a\cos i}{R_*}.$$

$$\frac{d\Omega}{4\pi} = \frac{2\pi \sin i \, di}{4\pi} = \frac{d(\cos i)}{2}.$$

$$\Pr\left(\cos i < \frac{R_* + R_p}{a}\right) = \frac{1}{2}\int_{-(R_*+R_p)/a}^{(R_*+R_p)/a} = \frac{R_* + R_p}{a}.$$

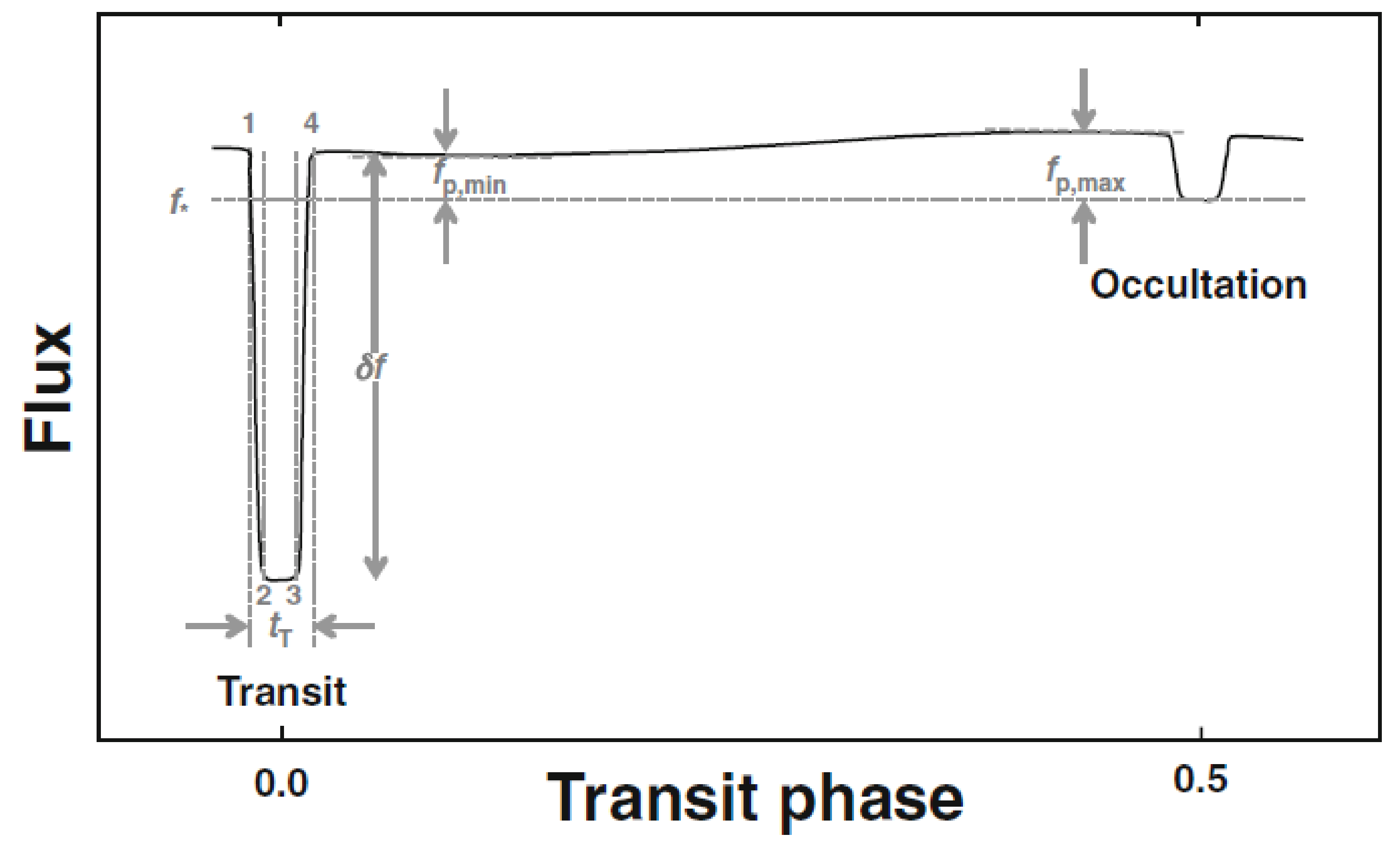
$$R_p \ll R_*,$$

$$\Pr\left(\cos i < \frac{R_*}{a}\right) =\simeq 0.0046\left(\frac{R_*}{R_\odot}\right)\left(\frac{1\,\mathrm{au}}{a}\right).$$

Selection in favour of close-in planets.

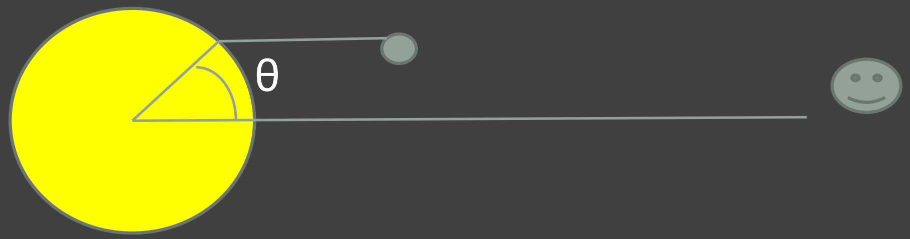
Andrew Cameron (in Bozza et al. 2016)

Transit depth



$$\frac{\Delta f}{f} \simeq \left(\frac{R_p}{R_*}\right)^2 = 0.0105 \left(\frac{R_p}{R_{Jup}}\right)^2 \left(\frac{R_*}{R_\odot}\right)^{-2}$$

Limb darkening



$\mu = \cos\theta$ = $\sqrt{1-b^2}$

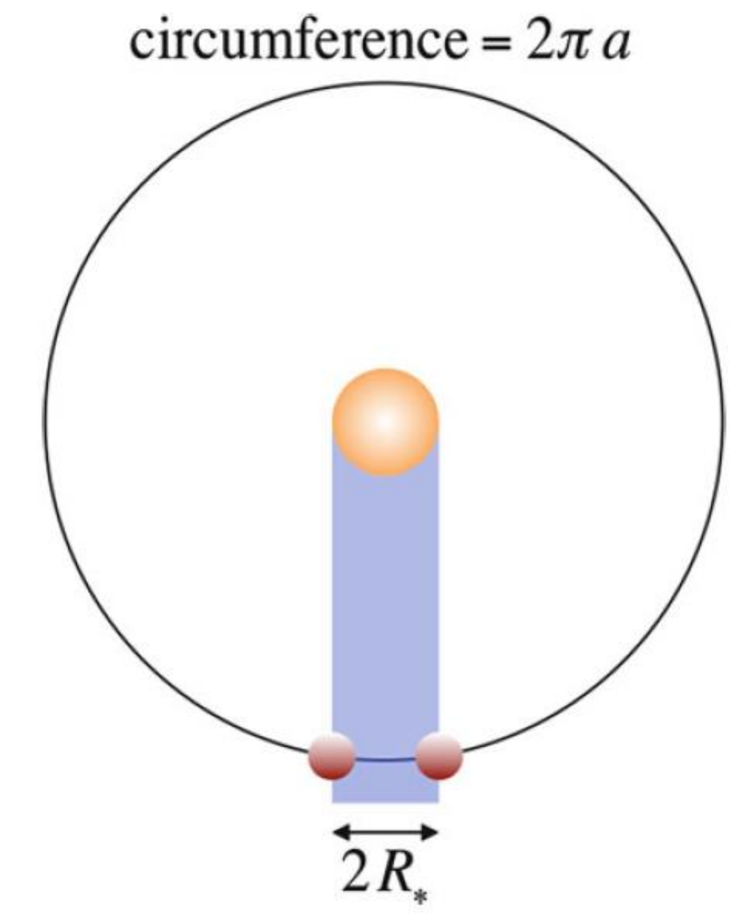
$$I = I_0(1 - u(1-\mu))$$

$$\frac{\Delta f}{f} = \frac{\pi R_{\mathrm{p}}^2 I_0 (1 - u + u\cos\theta)}{2\pi R_*^2 I_0 \int_0^{\pi/2} (1 - u + u\cos\theta)\sin\theta\cos\theta d\theta} = \frac{3(1 - u + u\sqrt{1-b^2})}{3-u}\left(\frac{R_{\mathrm{p}}}{R_*}\right)^2.$$

Limb darkening can be taken into account in a more precise manner

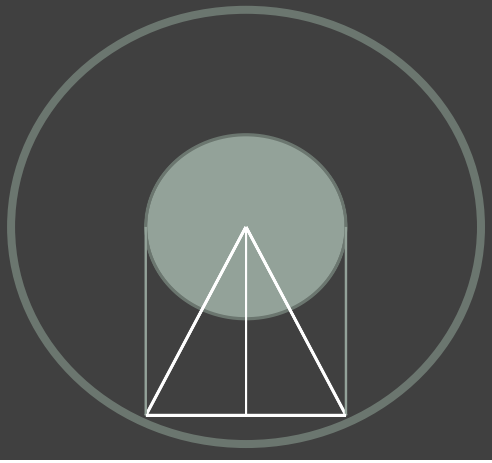
$$\frac{I(\mu)}{I_0} = 1 - \sum_{n=1}^{4} u_n (1 - \mu^{n/2}).$$

Transit duration



$$\frac{T}{P} = \frac{1}{\pi} \sin^{-1} \frac{R_*}{a}$$

$$\frac{T}{P} = \frac{1}{\pi} \sin^{-1} R_* \left(\frac{4\pi^2}{GM_* P^2} \right)^{1/3}$$



$$\frac{t_T}{P} = \frac{1}{\pi} \sin^{-1} \left(\frac{R_*}{a} \left\{ \frac{[1 + (R_\mathrm{p}/R_*)]^2 - [(a/R_*)\cos i]^2}{1 - \cos^2 i} \right\}^{1/2} \right)$$

t_T – from first to last contact

For $\cos i \ll 1$

$$\frac{t_T}{P} = \frac{R_*}{\pi a} \sqrt{\left(1 + \frac{R_\mathrm{p}}{R_*}\right)^2 - b^2}.$$

Andrew Cameron (in Bozza et al. 2016)

System parameters

$$T \simeq 3\mathrm{h}\left(\frac{P}{4\mathrm{d}}\right)^{1/3}\left(\frac{\rho_*}{\rho_\odot}\right)^{-1/3}$$

Stellar density estimate

$$\frac{dv_\mathrm{r}}{dt} = \frac{2\pi K}{P} = \frac{GM_\mathrm{p}}{a^2} = g_\mathrm{p}\frac{R_\mathrm{p}^2}{a^2} = g_\mathrm{p}\frac{R_\mathrm{p}^2}{R_*^2}\frac{R_*^2}{a^2},$$

K – stellar velocity

$$g_\mathrm{p} = \frac{2\pi K}{P}\left(\frac{R_*}{R_\mathrm{p}}\right)^2\left(\frac{a}{R_*}\right)^2$$

Planet density

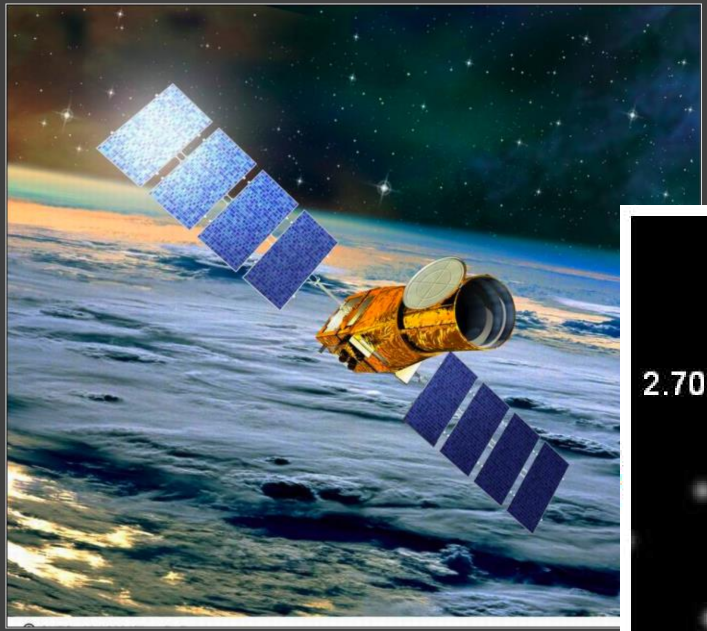
$$\rho_\mathrm{p} = \frac{3g_\mathrm{p}}{4\pi GR_\mathrm{p}} = \frac{3g_\mathrm{p}}{4\pi GR_*}\left(\frac{R_*}{R_\mathrm{p}}\right)$$

$$R_* = \theta d = \theta/\hat{\pi}:$$

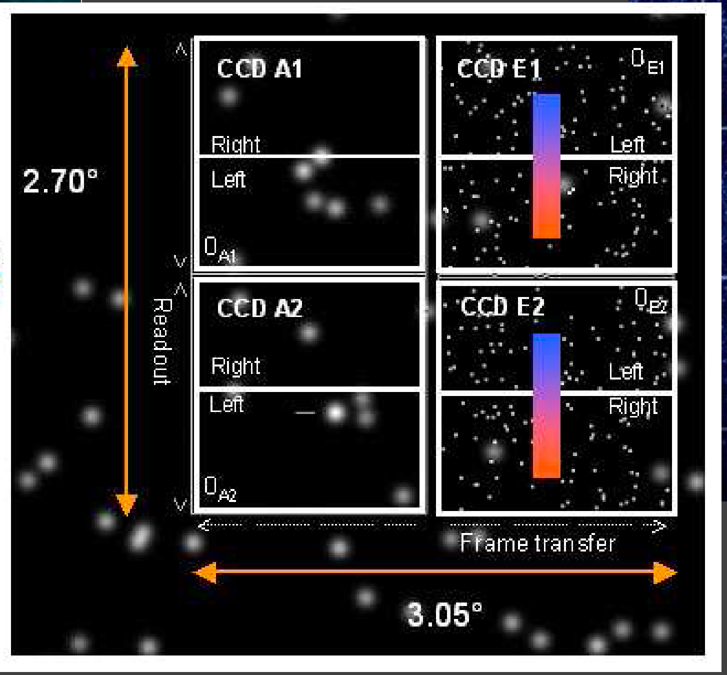
$$\rho_\mathrm{p} = \frac{3g_\mathrm{p}\hat{\pi}}{4\pi G\theta}\left(\frac{R_*}{R_\mathrm{p}}\right)$$

CoRoT

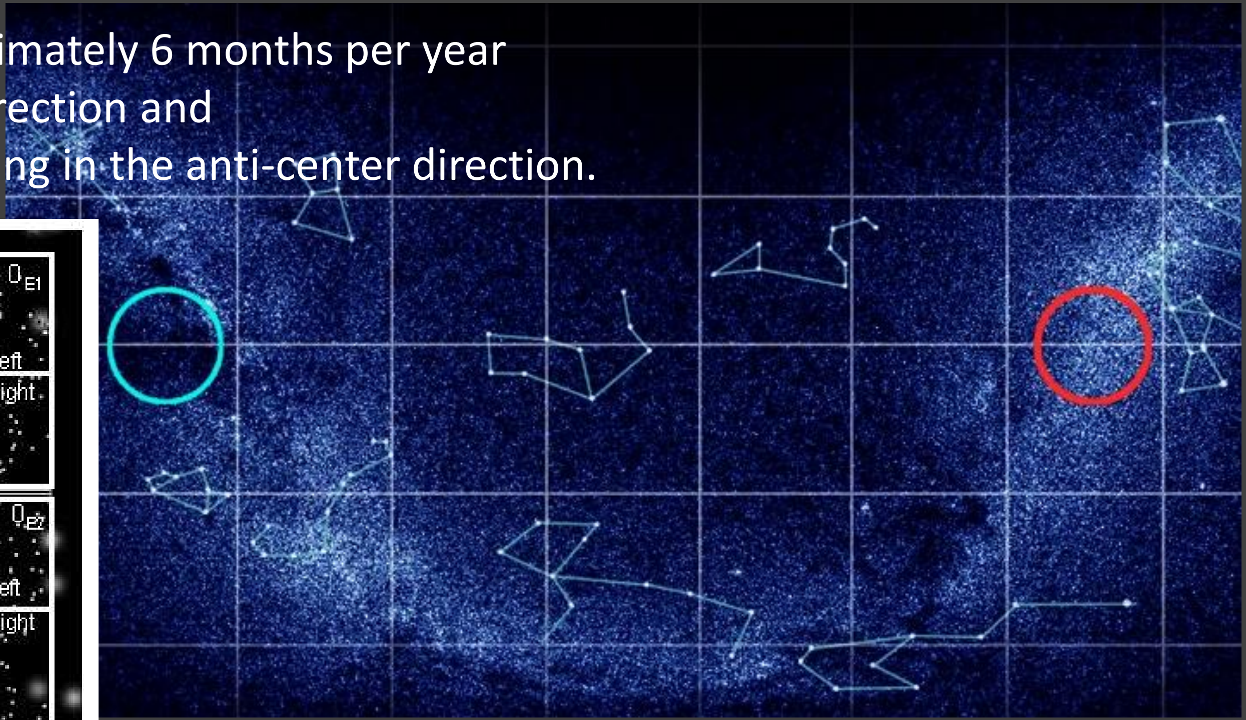
December 2006 – November 2012
27-cm telescope



The satellite spent approximately 6 months per year observing in the center direction and
6 months per year observing in the anti-center direction.



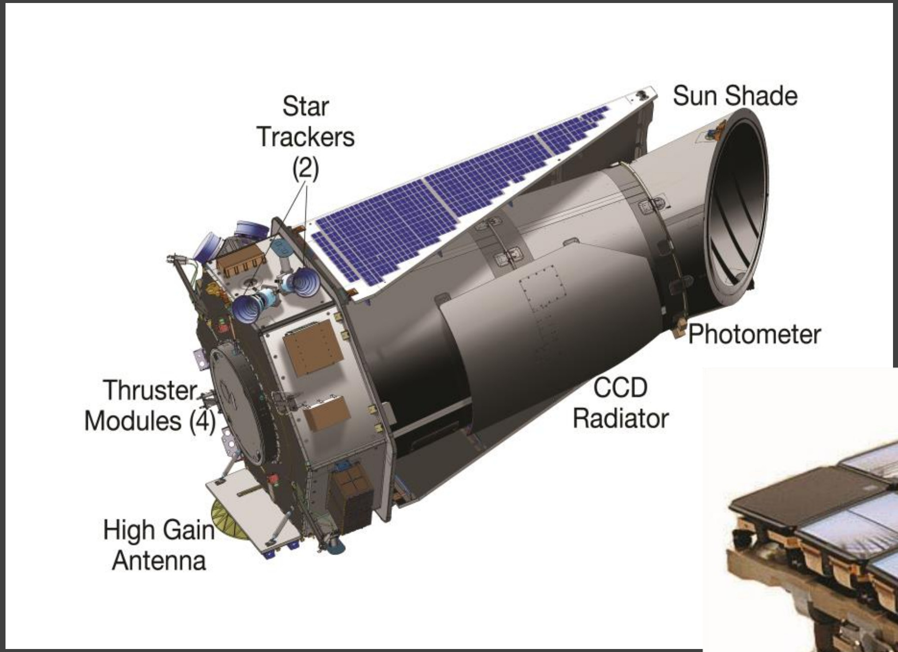
Focal planet arrangement
of the asteroseismology (A1, A2)
and the exoplanet (E1, E2) CCDs.



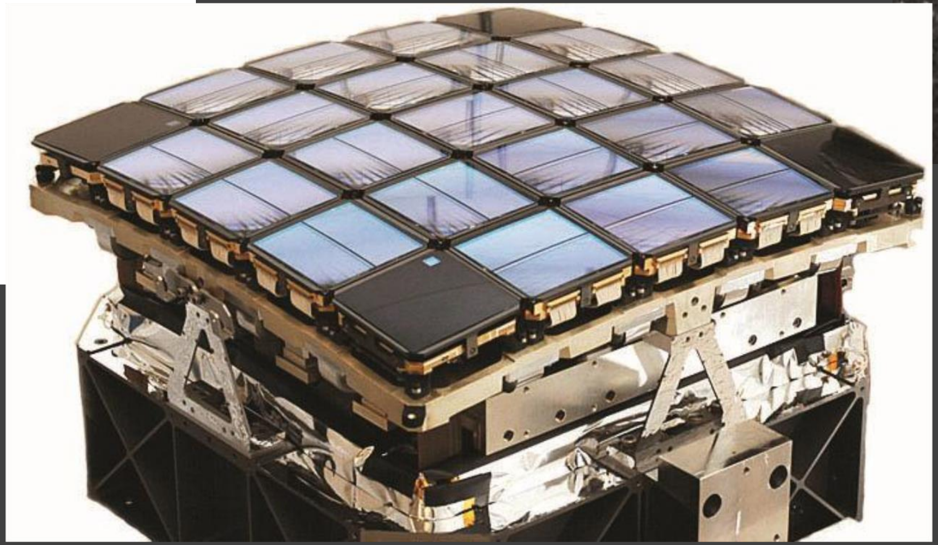
Position of the CoRoT eyes in the sky.
The blue and red circles represent the center
and anti-center.

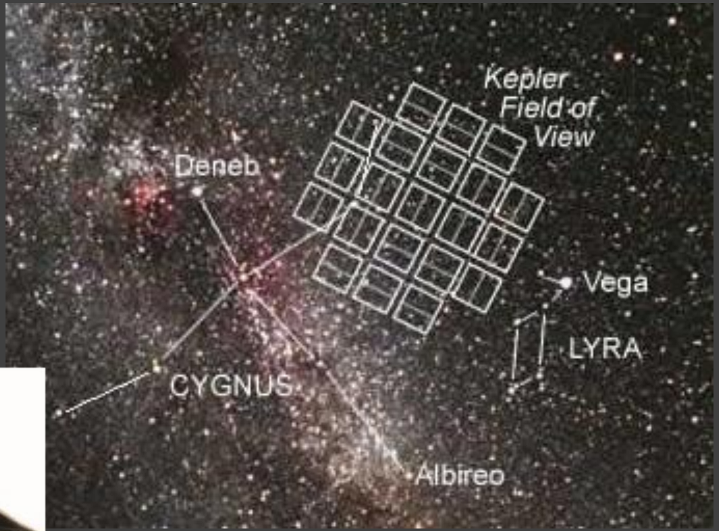
Kepler

2009-2013 + K2-mission
0.95 m telescope



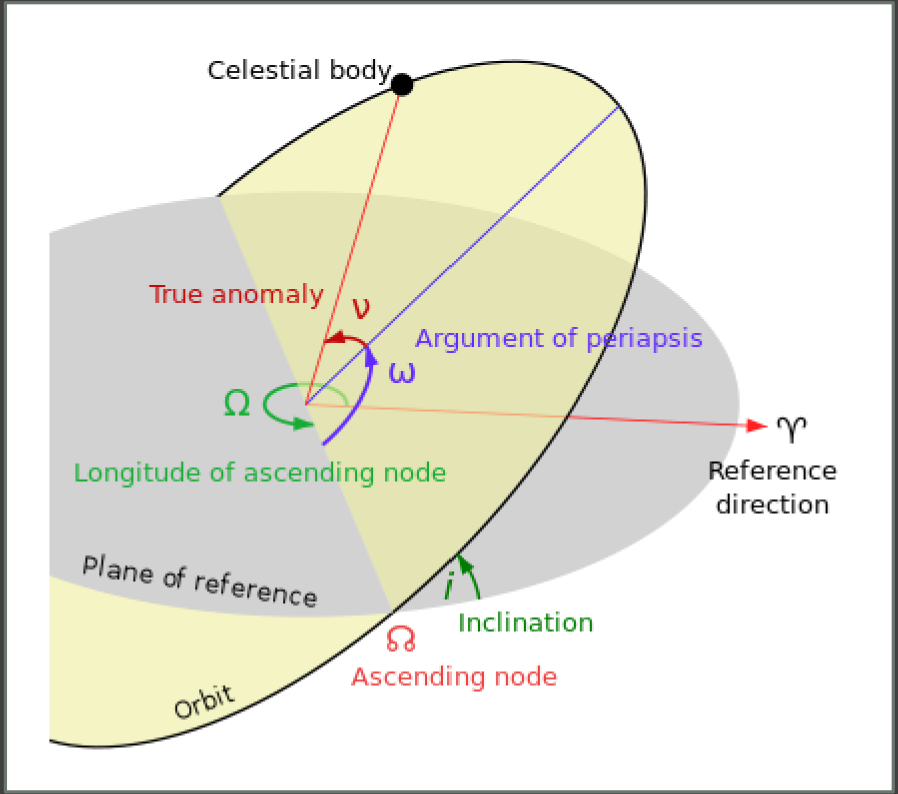
Monitoring of ~150 000 stars





Field of view ~115 sq. degrees

Orbital elements

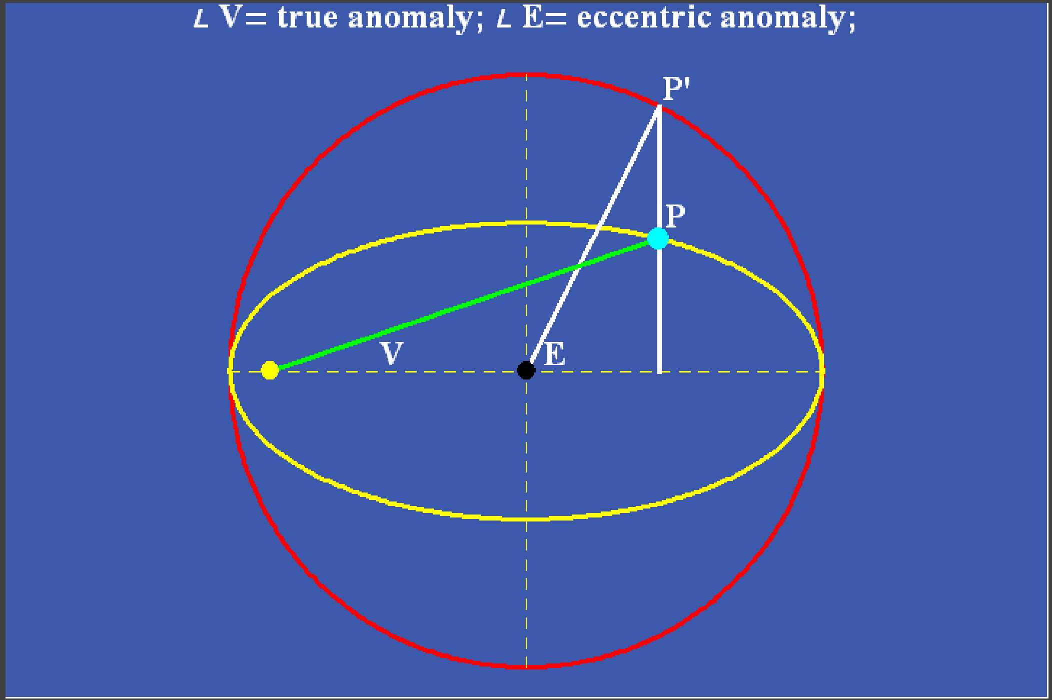


ν – true anomaly

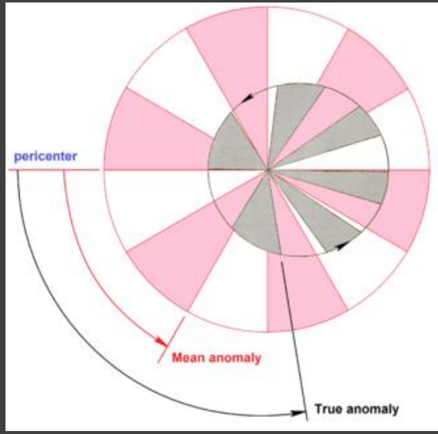
ω – argument of periastron

E - eccentric anomaly

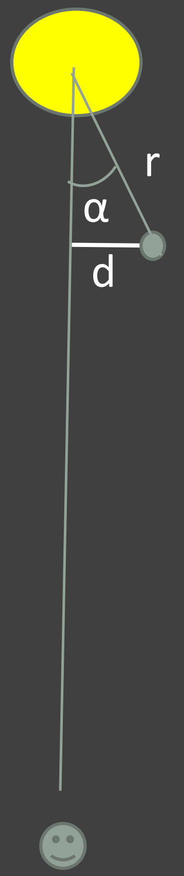
M – mean anomaly



http://www.wlym.com/antidummies/part66.html

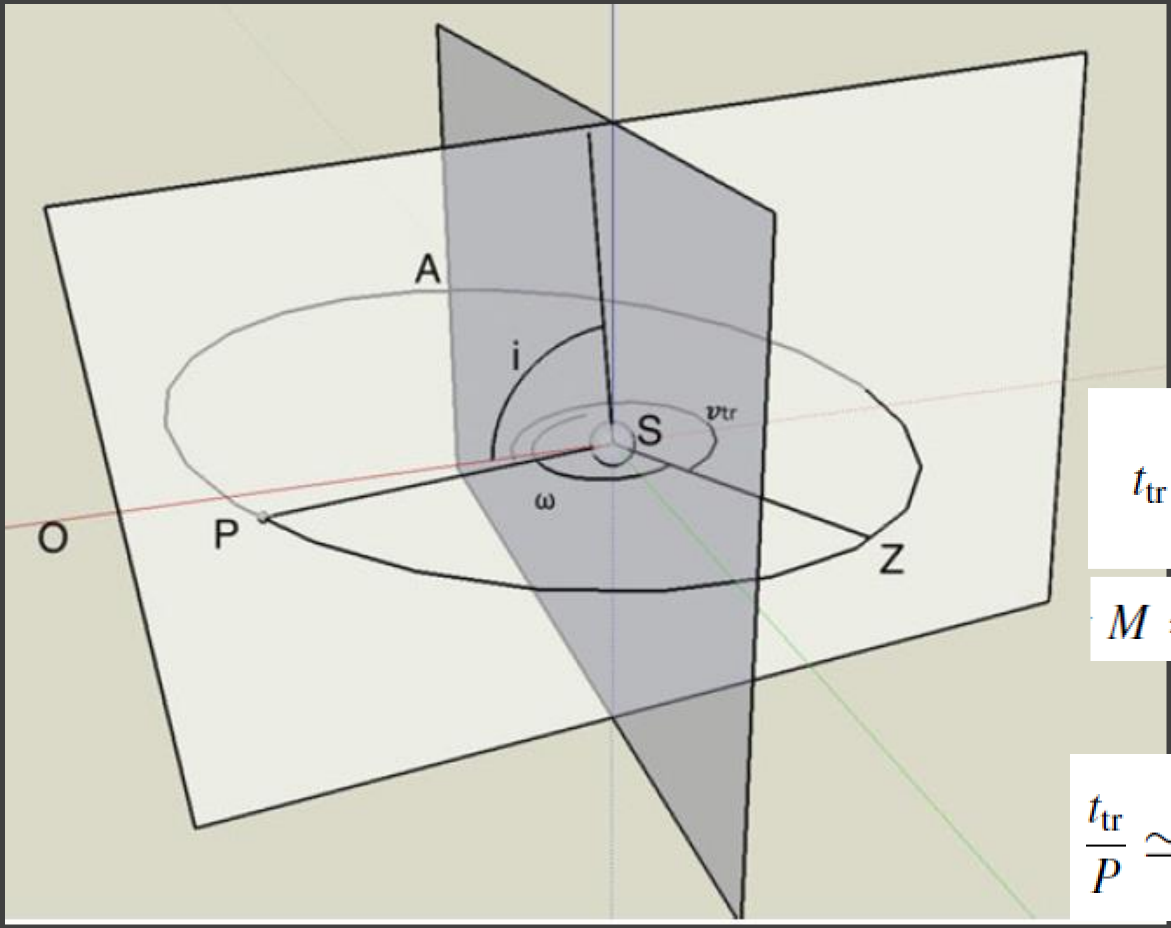


Orbital parameters



d=r sin α
z=d/R_{star}

p=R_p/R_{star}



$$\nu_{\mathrm{tr}} = \frac{\pi}{2} - \omega \qquad \nu_{\mathrm{occ}} = \frac{3\pi}{2} - \omega,$$

$$E = 2\tan^{-1}\left[\sqrt{\frac{1-e}{1+e}}\tan\frac{\nu}{2}\right]$$

$$t_{\mathrm{tr}} - t_0 = \frac{P}{2\pi}M_{\mathrm{tr}} = \frac{P}{2\pi}(E_{\mathrm{tr}} - e\sin E_{\mathrm{tr}}).$$

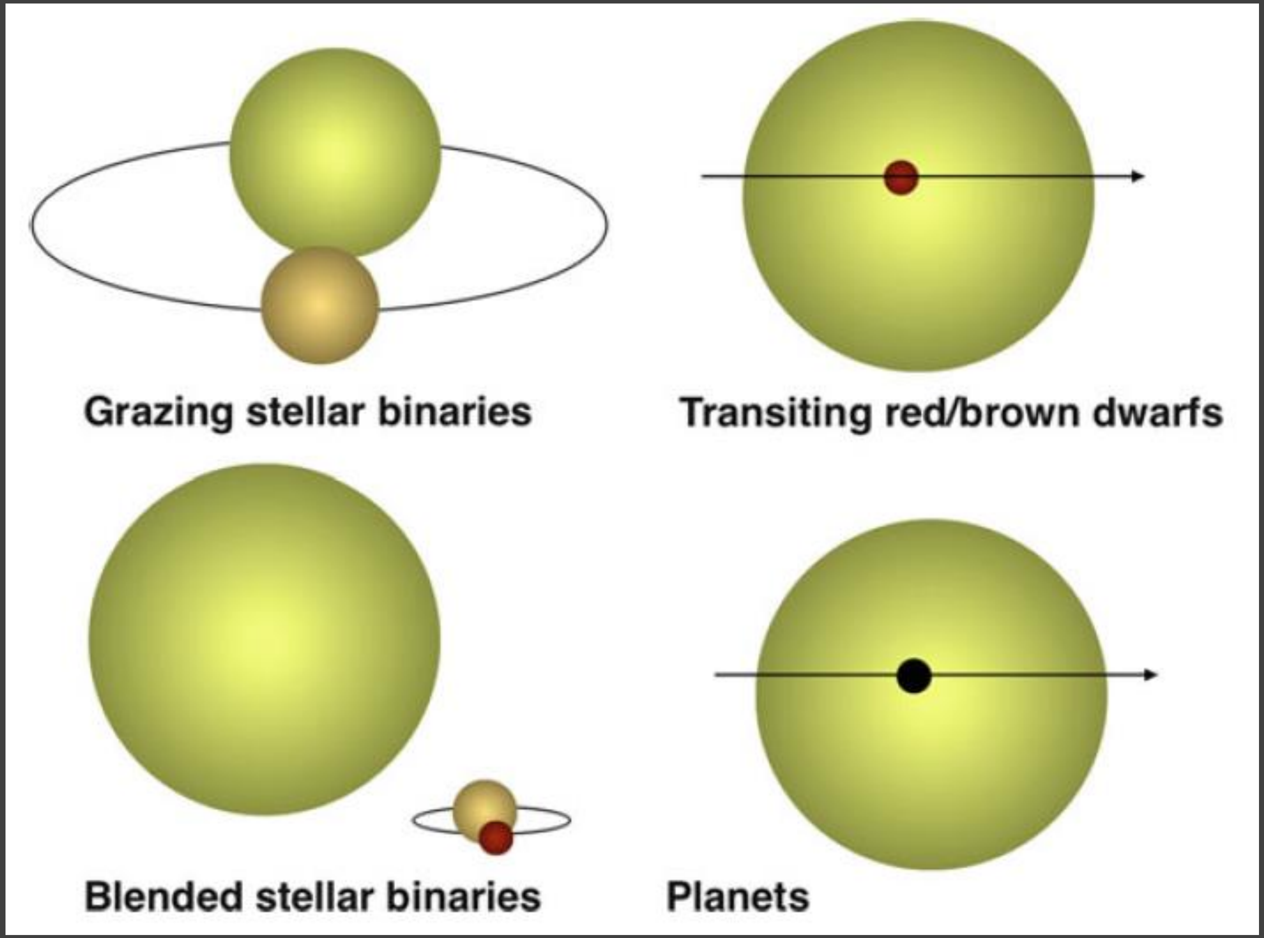
$$M = E - e\sin E. \qquad E_{i+1} = M + e\sin E_i.$$

$$E_1 = M,$$

$$\frac{t_{\mathrm{tr}}}{P} \simeq \frac{R_*}{a}\frac{\sqrt{(1+R_{\mathrm{p}}/R_*)^2 - b^2}}{\pi}\frac{1+e\sin\omega}{1-e^2}.$$

Andrew Cameron (in Bozza et al. 2016)

Transits and transit-like events



Spectral lines and planet/star mass ratio

$$\dot{v}_{\mathrm{r}} \simeq \frac{GM_*}{a^2} = \frac{2\pi K}{P}\frac{M_*}{M_{\mathrm{p}}}.$$

Observations of spectral line in the planet atmosphere can allow to measure important parameters of the system!

Measurements of the radial acceleration (due to observations of spectral lines in the planet atmosphere) allow to measure stellar mass.

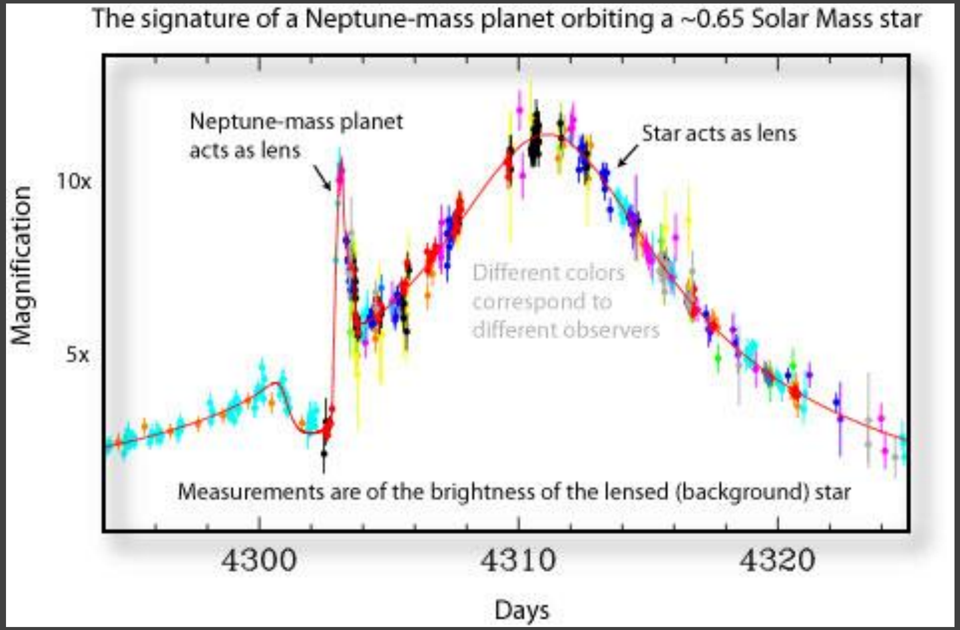
$$\frac{T}{P} = \frac{1}{\pi}\sin^{-1}\frac{R_*}{a}$$

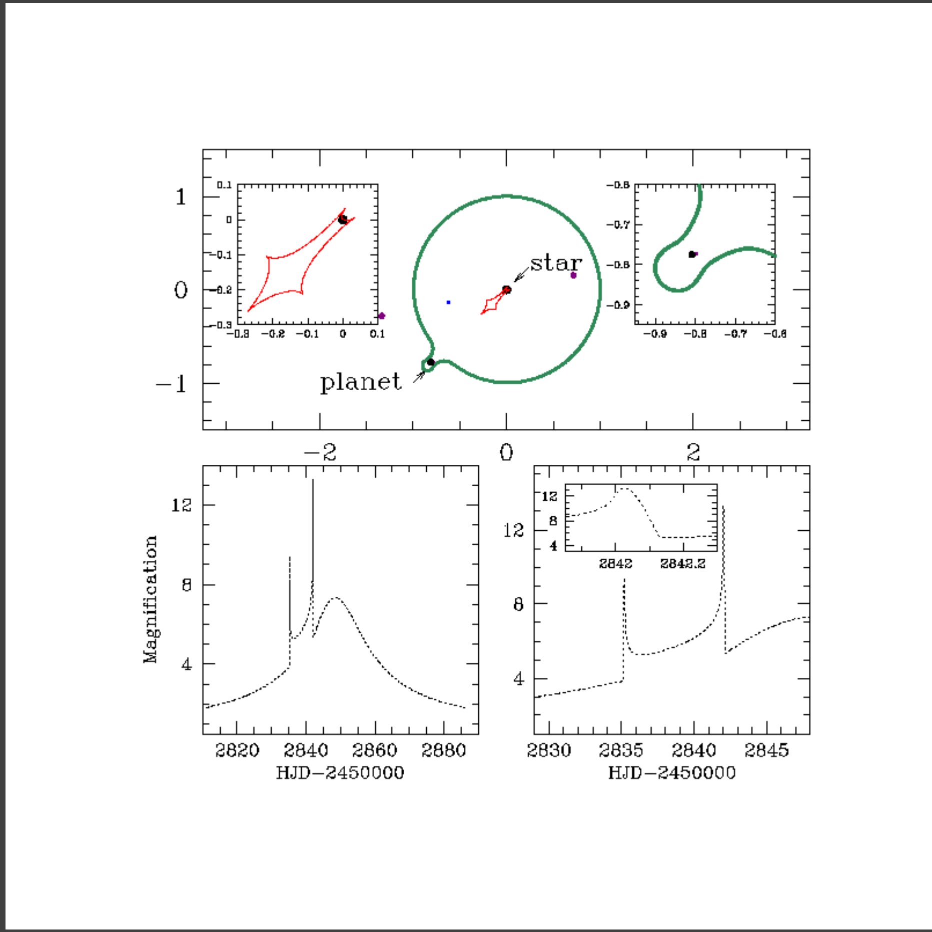
$$\delta v_{\mathrm{r}} \simeq \frac{P}{\pi}\frac{R_*}{a}\frac{2\pi K}{P}\frac{M_*}{M_{\mathrm{p}}}.$$

If narrow spectral lines in the planet atmosphere can be observed during transit then it is possible to derive M_{star}/M_{planet}

Exoplanet detection via microlensing

- Sensitive to low mass planets (down to 0.1 M_{earth})
- Sensitive to wide orbits (1-4 AU)
- Sensitive to free-floating planets

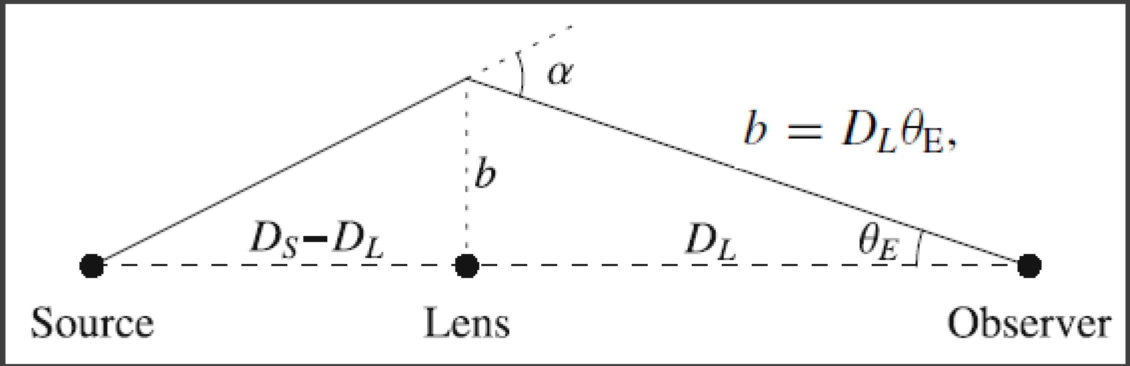




https://www3.nd.edu/~bennett/moa53-ogle235/technical.gif

See a review in Bennet 0902.1761

Gravitational microlensing - 1



$$\alpha = b/D_L + b/(D_S - D_L).$$

$$\theta_\mathrm{E} = \sqrt{\kappa M \pi_\mathrm{rel}}; \qquad \kappa \equiv \frac{4G}{c^2\mathrm{AU}} \simeq 8.14 \frac{\mathrm{mas}}{M_\odot},$$

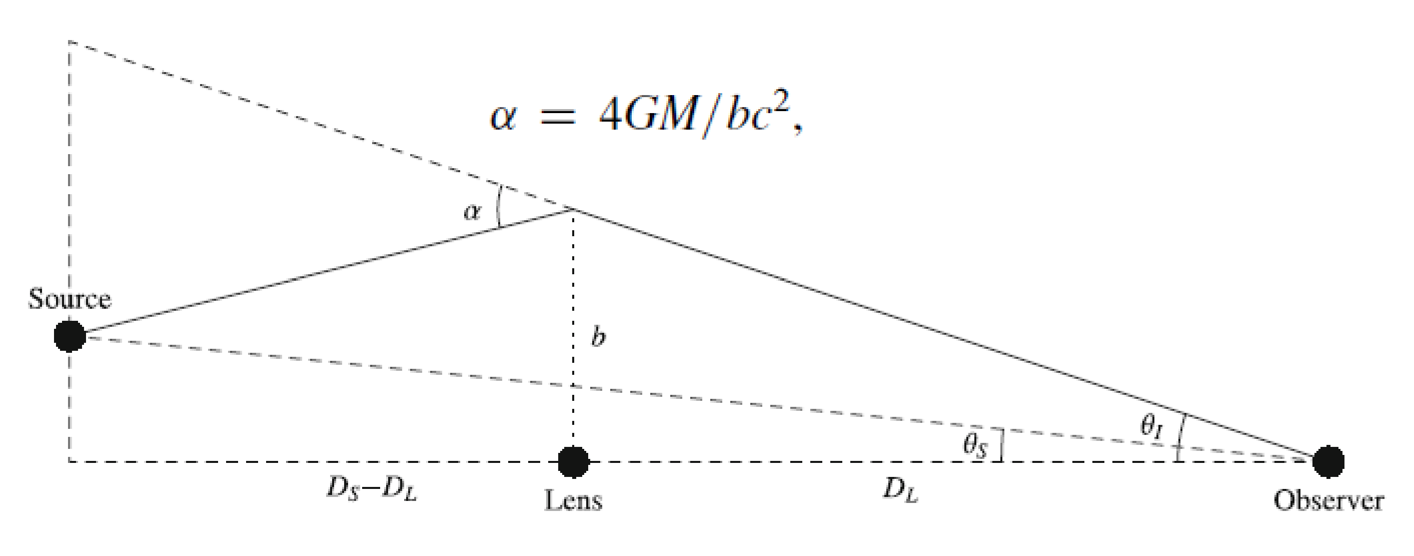
$$\pi_\mathrm{rel} = \mathrm{AU}(D_L^{-1} - D_S^{-1})$$

Probability of microlensing is small.
For stars it is ~10^{-5} – 10^{-6} per year.
For planets it is lower, as $\theta_E \sim M^{1/2}$
and $M_{planet}/M_{star} \sim 10^{-4}$

$$\tau = \int dD_L \pi (D_L \theta_\mathrm{E})^2 n(D_L) \sim \frac{4\pi G M n}{c^2} D^2 = \frac{4\pi G \rho}{c^2} D^2 \sim \frac{G M_\mathrm{tot}}{D c^2} \sim \frac{v^2}{c^2}$$

Andrew Gould (in Bozza et al. 2016)

Gravitational microlensing - 2



$$(\theta_I - \theta_S)D_S = \alpha(D_S - D_L)$$

$$\theta_I(\theta_I - \theta_S) = \frac{4GM\pi_{\rm rel}}{c^2\,\mathrm{AU}} \equiv \theta_{\rm E}^2.$$

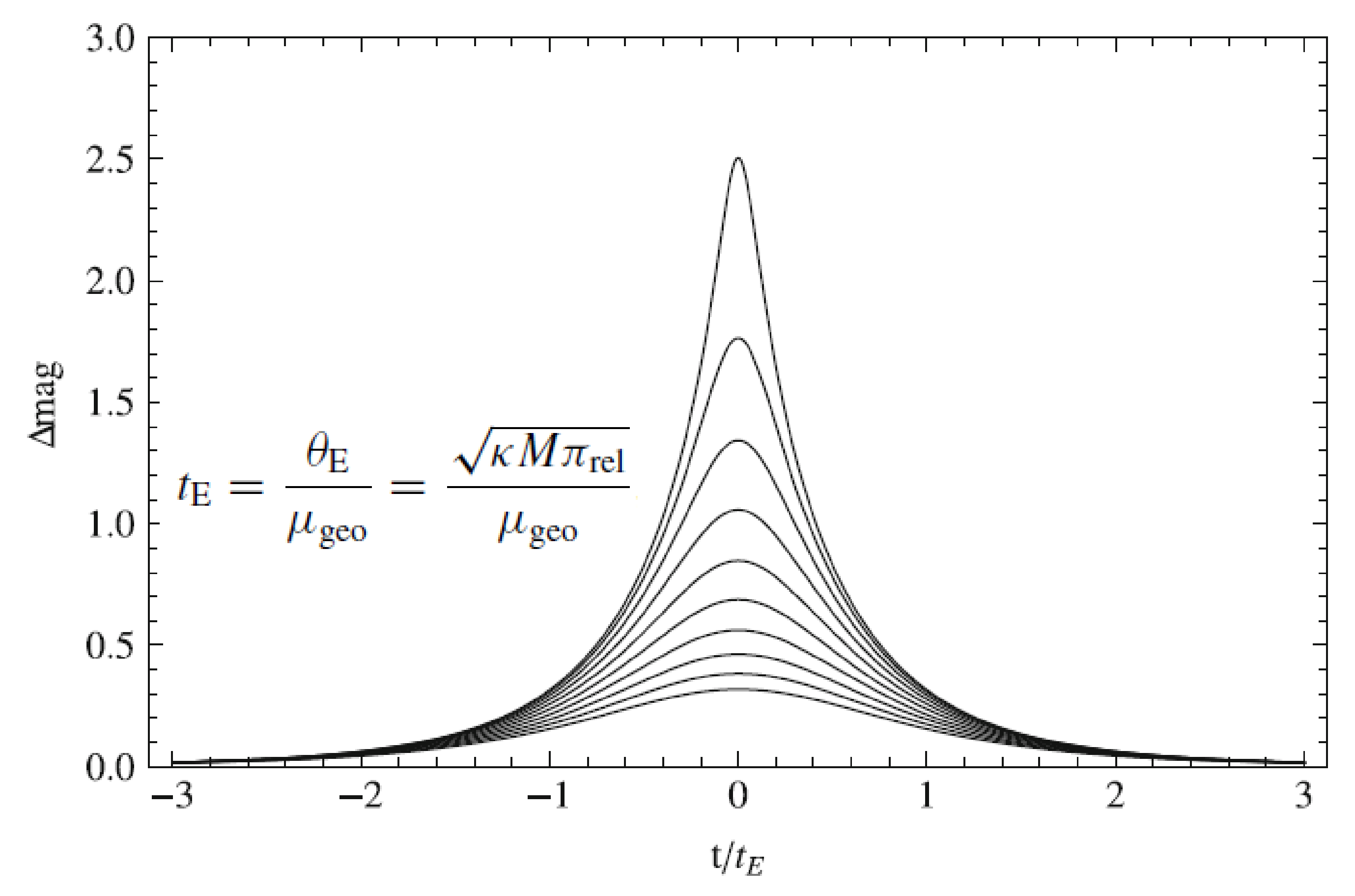
$$u_\pm = \frac{u \pm \sqrt{u^2+4}}{2}; \qquad u \equiv \frac{\theta_S}{\theta_{\rm E}} \qquad u_\pm \equiv \frac{\theta_{I,\pm}}{\theta_{\rm E}}.$$

$$A_\pm = \pm\frac{u_\pm}{u}\frac{\partial u_\pm}{\partial u} = \frac{A \pm 1}{2}$$

$$A = \frac{u^2+2}{u\sqrt{u^2+4}} = (1 - Q^{-2})^{-1/2}; \qquad Q \equiv 1 + \frac{u^2}{2},$$

Andrew Gould (in Bozza et al. 2016)

Light curves for point lenses



$$F(t) = f_s A(\mathbf{u}(t; t_0, u_0, t_{\mathrm{E}}), \rho) + f_b;$$

$$\mathbf{u}(t; t_0, u_0, t_{\mathrm{E}}) = (\tau(t), \beta) = \left(\frac{t - t_0}{t_{\mathrm{E}}}, u_0\right).$$

Finite size lense

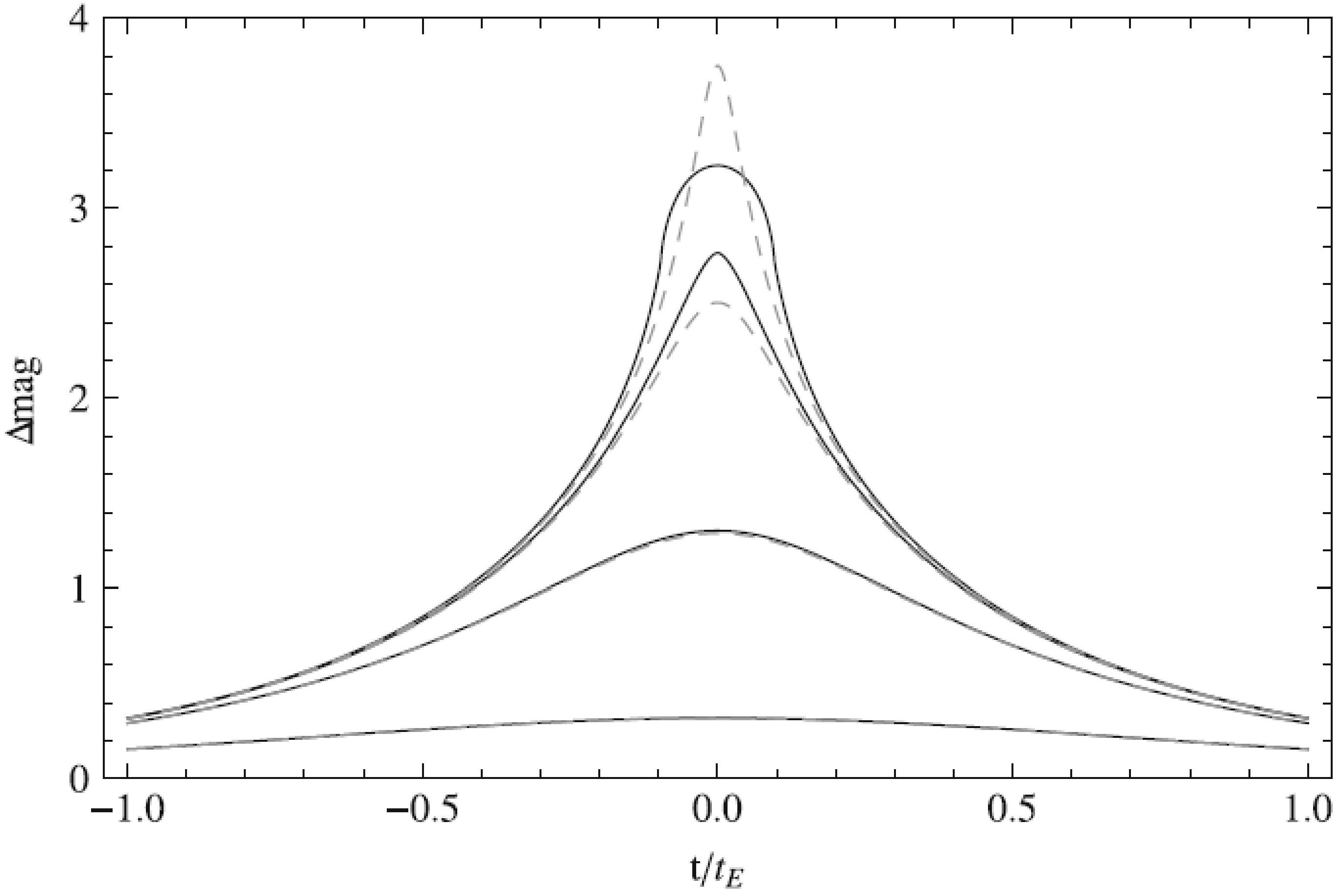


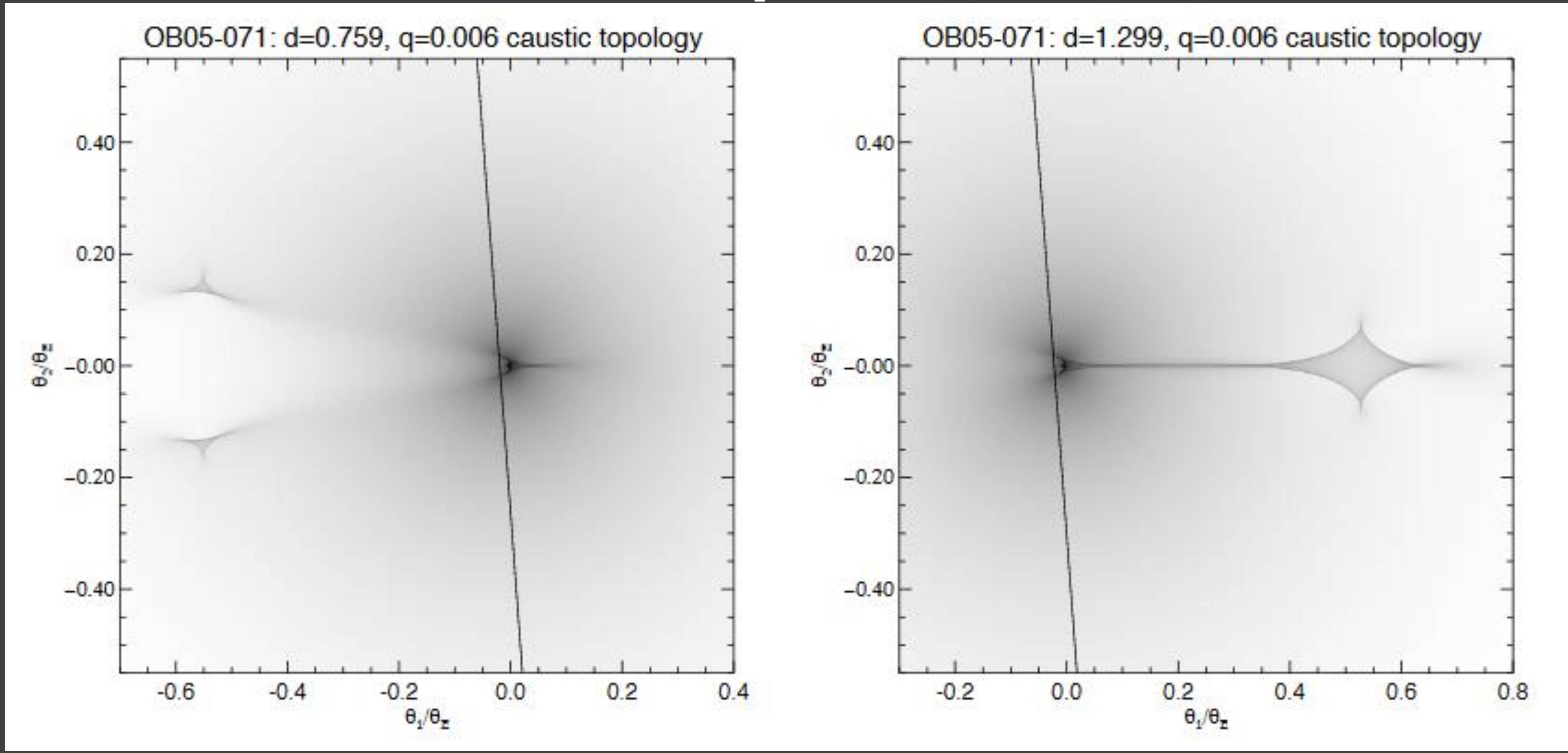
Fig. 3.4 Magnification as a function of time in microlensing events for an impact parameters $u_0 = 10^{-n}$ with $n \in \{-1.5, -1, -0.5, 0\}$. The angular source size is $0.1\theta_E$. Note that when the impact parameter is greater than the source radius, the magnification is higher than the corresponding Paczynski curve (*dashed*). When the impact parameter is smaller than the source radius (source passing right behind the lens), the magnification saturates

Binary lense

s – separation of components in units of the Einstein radius θ_E.

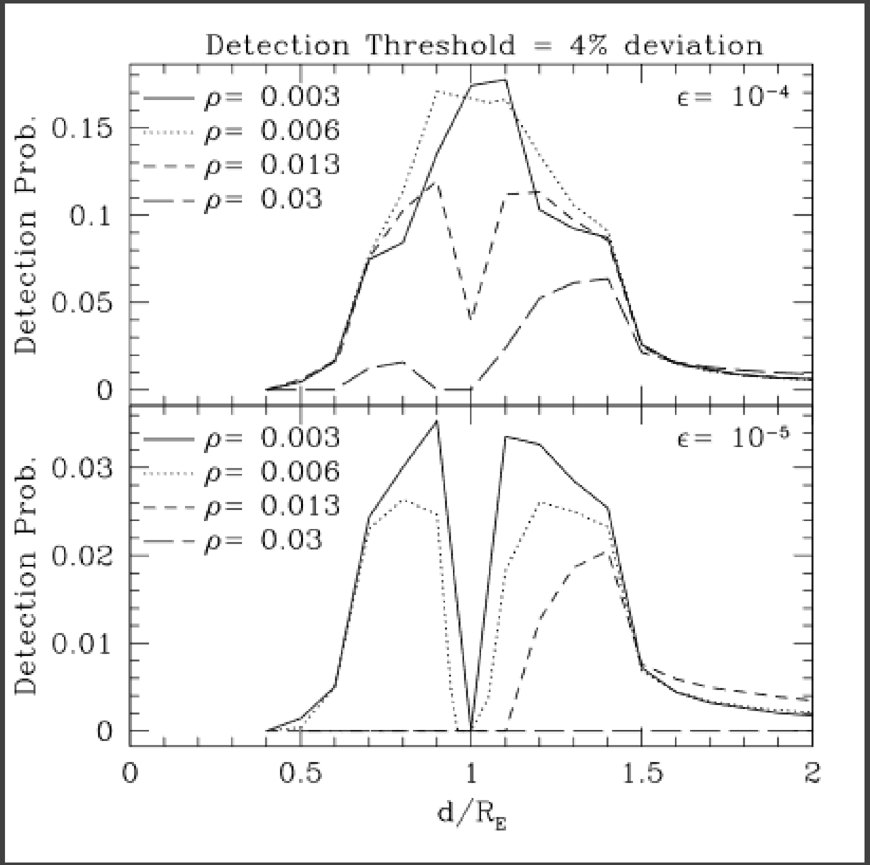
q - mass ratio.

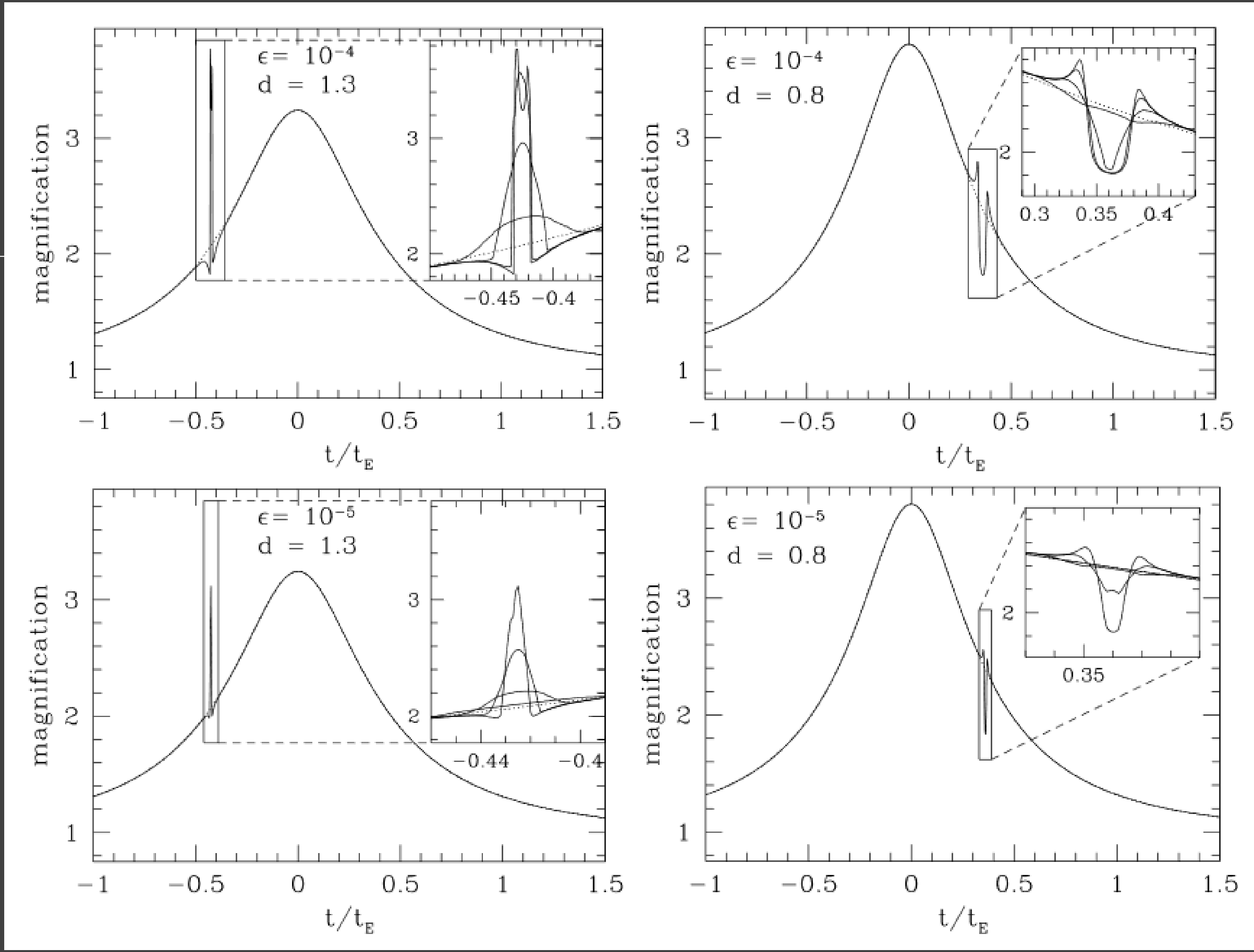
$$r_{\perp} = s\theta_{\mathrm{E}} D_L,$$



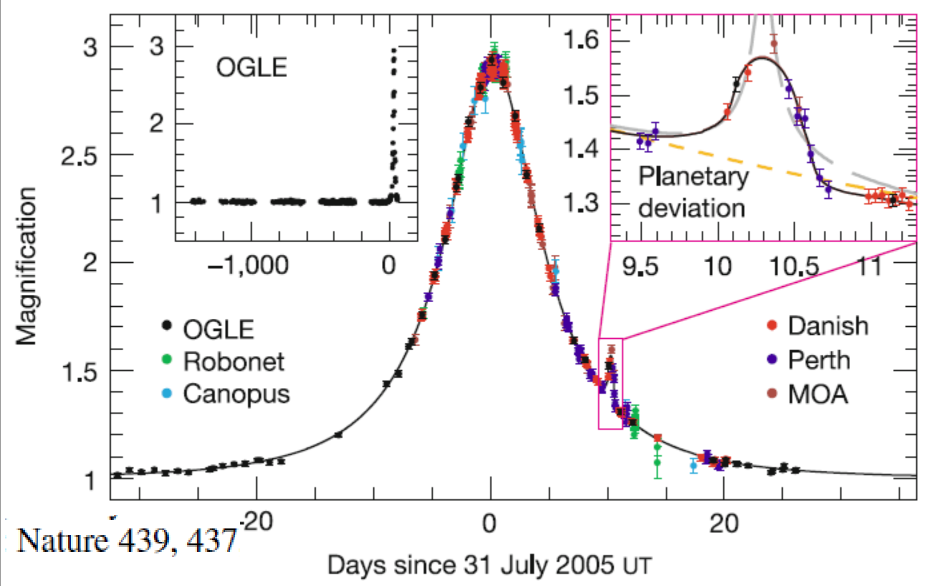
0902.1761

Light curves





Cold Neptune



Nature 439, 437

$$A_p = \frac{2}{\rho_p^2} = 2\left(\frac{\theta_{E,p}}{\theta_*}\right)^2$$

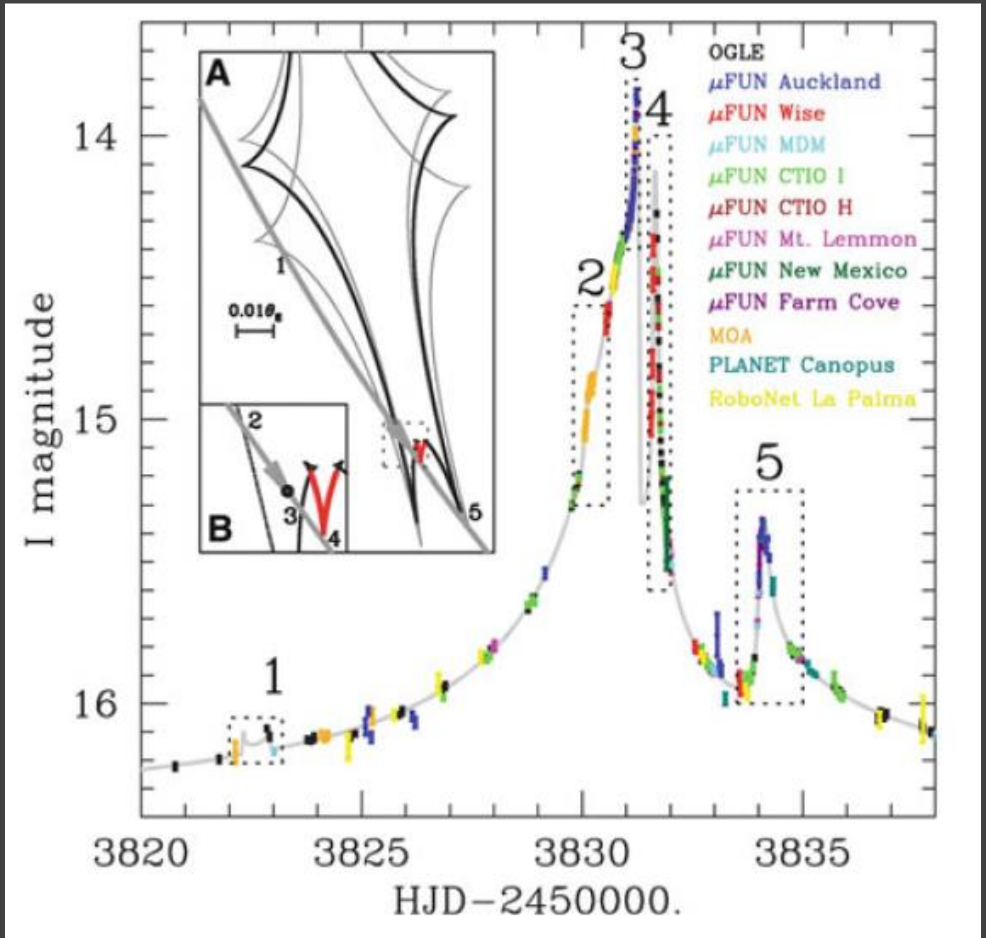
$$\frac{t_p}{t_E} = \frac{\theta_*}{\theta_E}.$$

$$q = \frac{m_p}{M} = \frac{\theta_{E,p}^2}{\theta_E^2} = \frac{\theta_{E,p}^2}{\theta_*^2}\frac{\theta_*^2}{\theta_E^2} = \frac{A_p}{2}\frac{t_p^2}{t_E^2} \simeq 1.0 \times 10^{-4}.$$

$$r_\perp = s\theta_E D_L = 2.2\,\mathrm{AU}\frac{D_L}{8\,\mathrm{kpc}}.$$

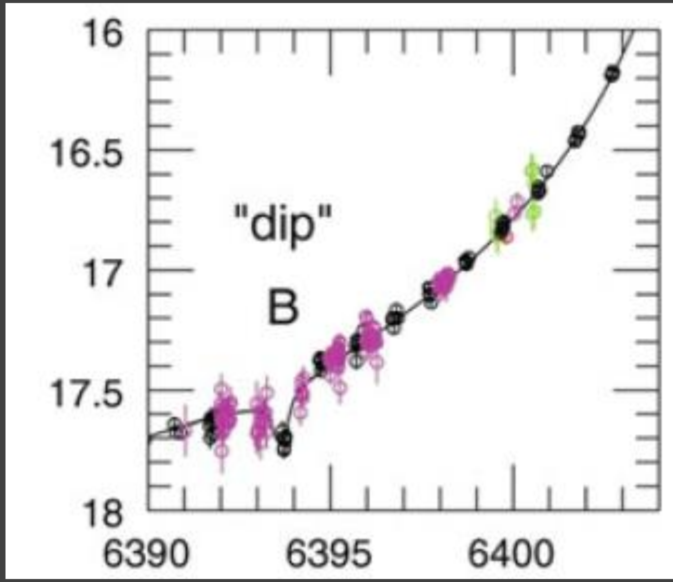
Andrew Gould (in Bozza et al. 2016)

Solar system – like system

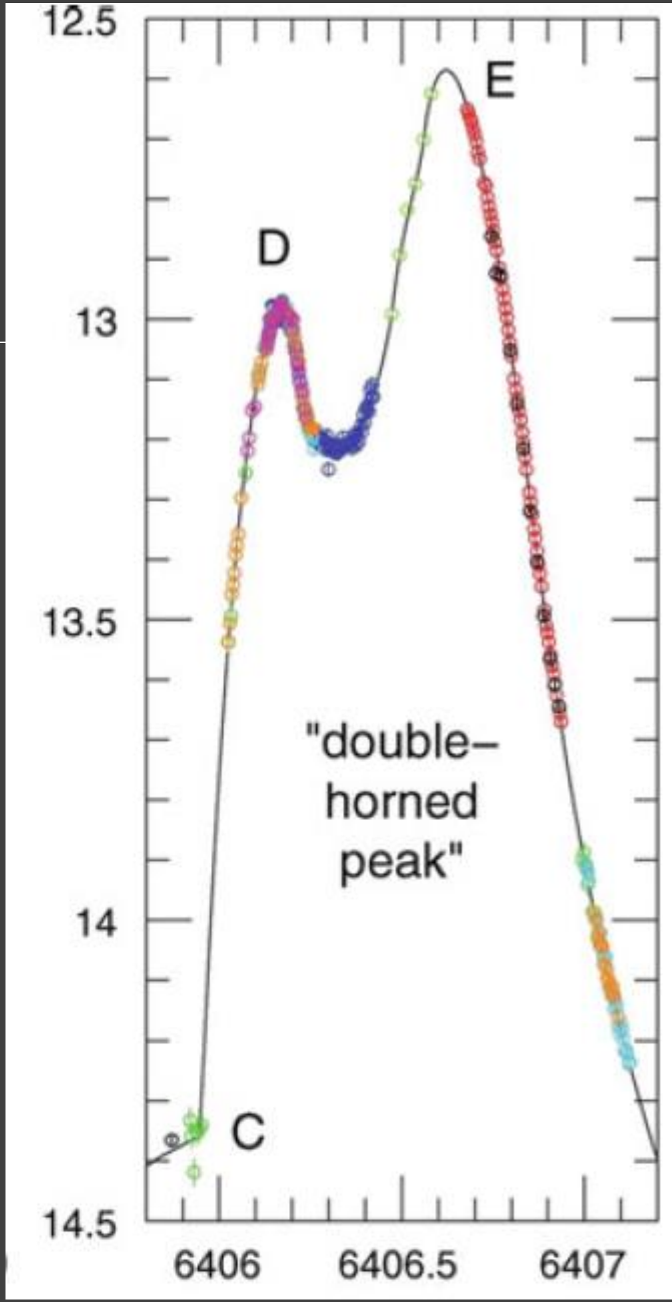


Jupiter and Saturn analogues. Distances are slightly smaller consistent with smaller mass of the host star.

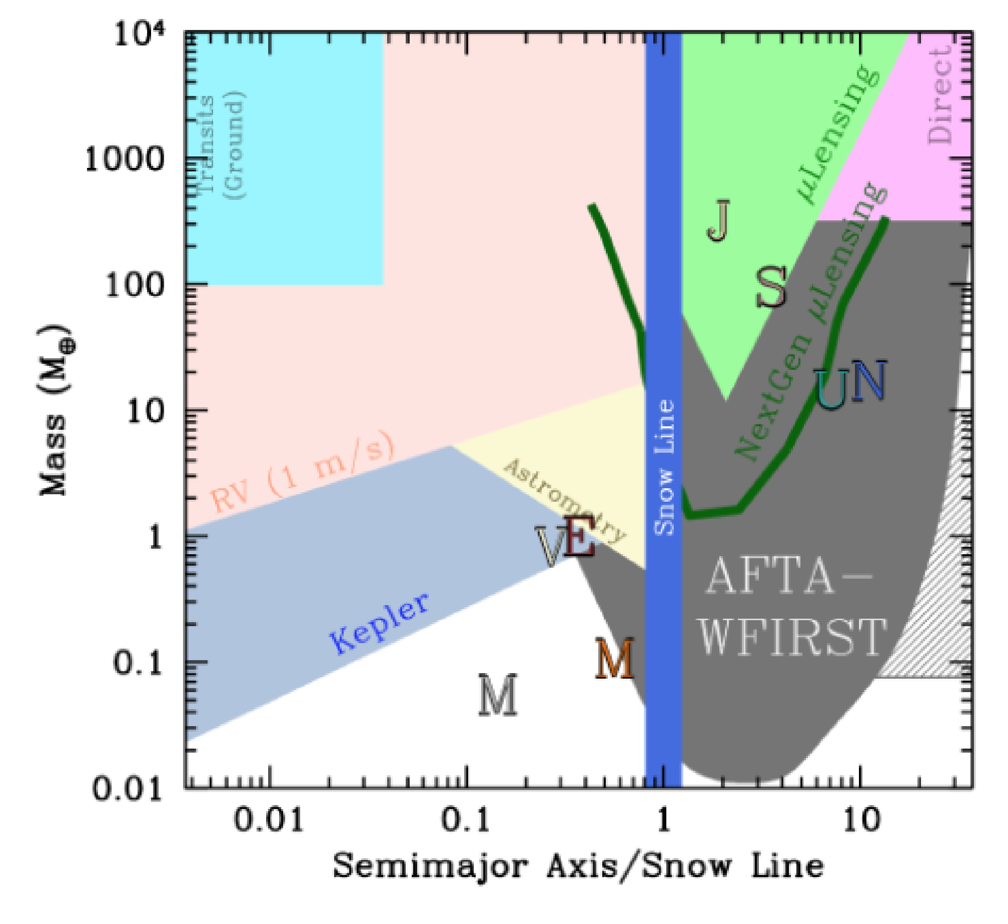
Dips due to planets



A terrestrial-mass planet in a binary. The planet orbits a red dwarf (1 AU), which orbits another star (15 AU)



Comparison of three methods



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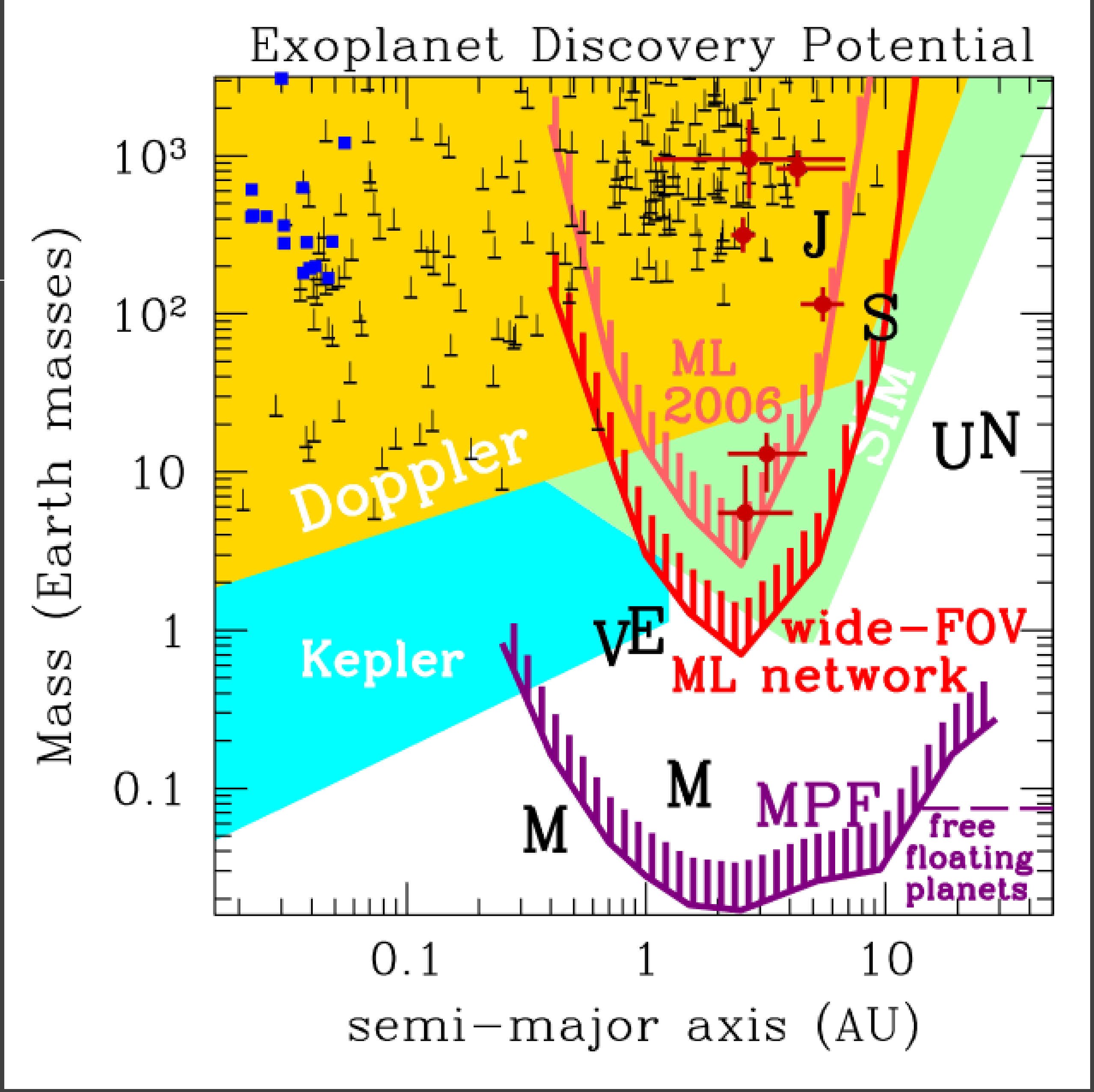

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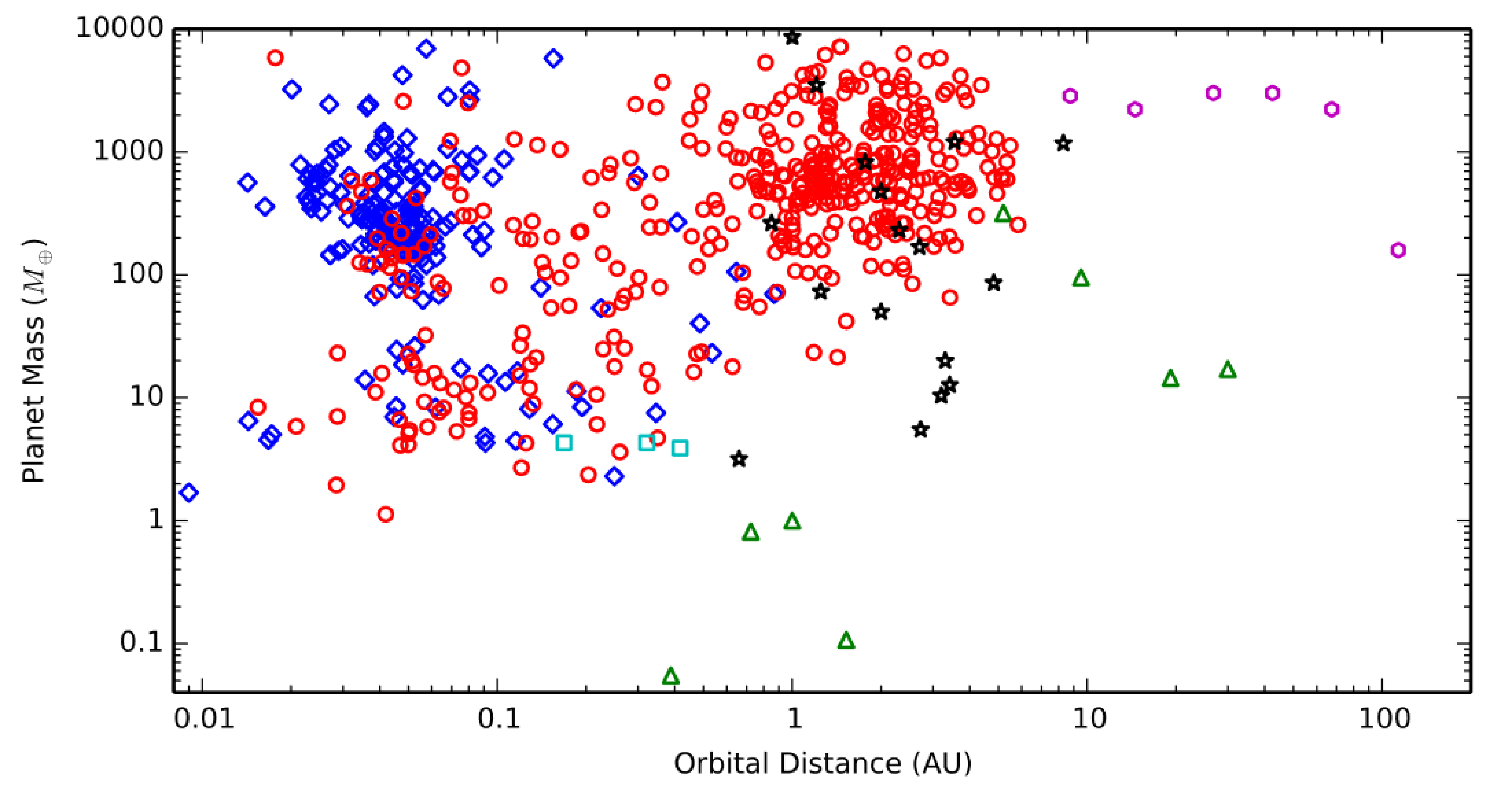
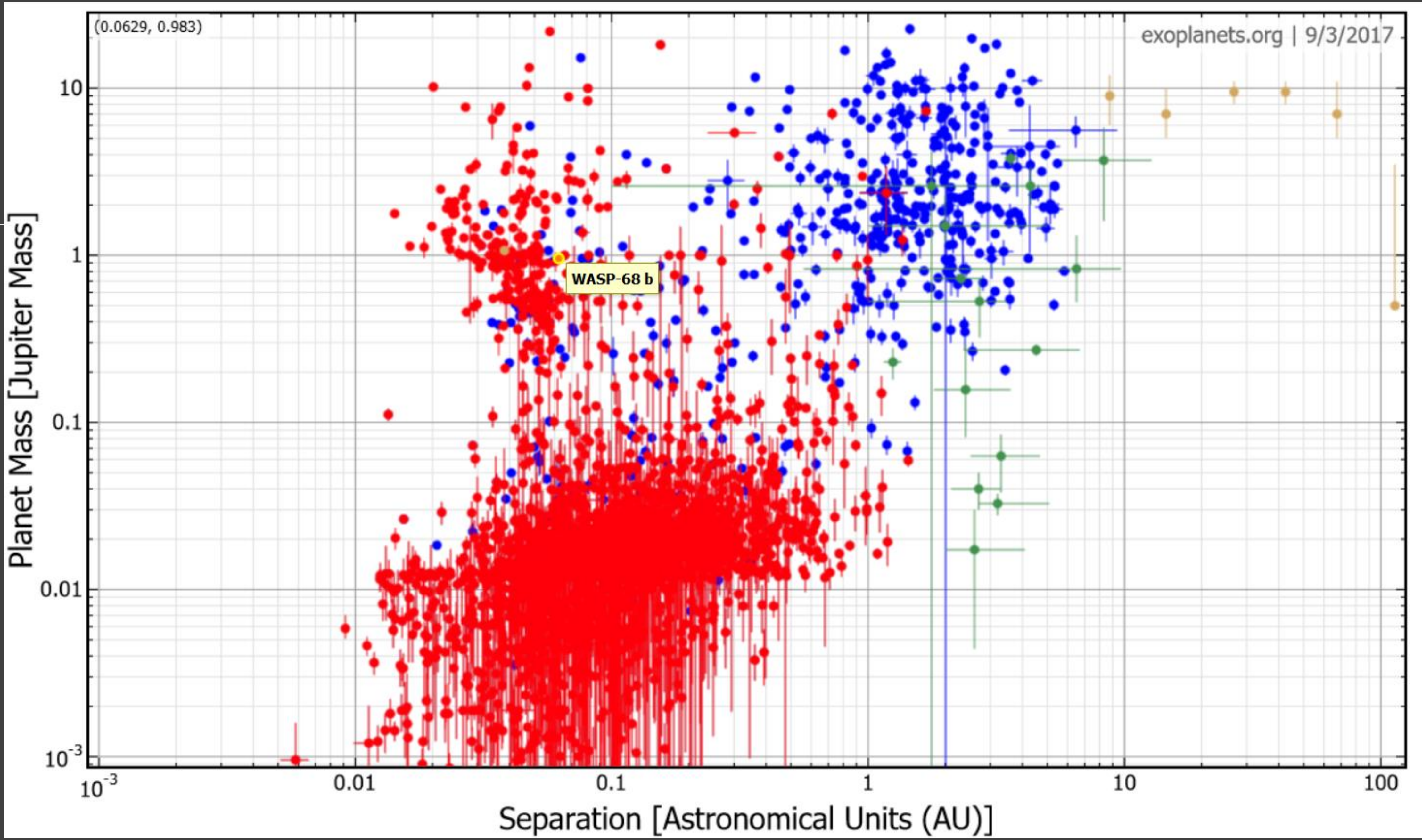
Discoveries by different methods



RV = red circles,
transit = blue diamonds,
imaging = magenta hex.,
gravlens = black stars,
psr time = cyan squares.

Planets in the Solar System are green triangles.

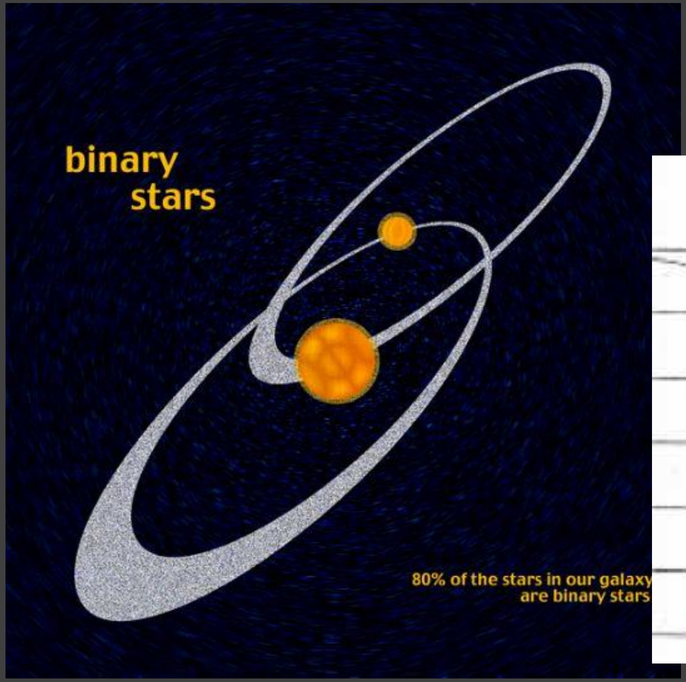
Blue- RV
Red – Trans.
Green – lense
Orange – imaging

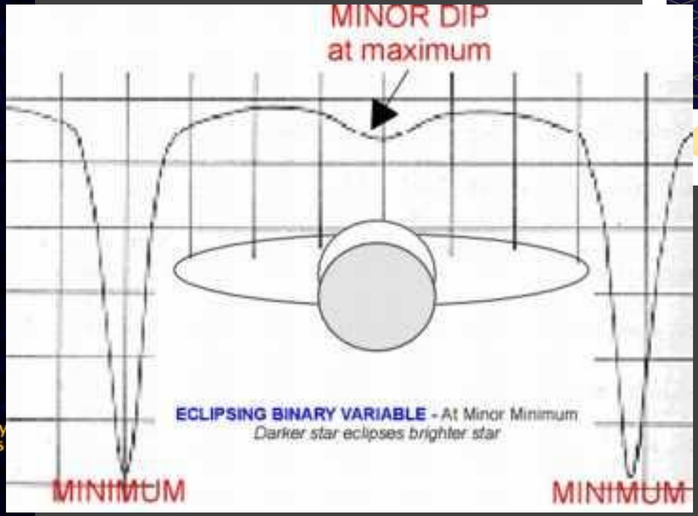


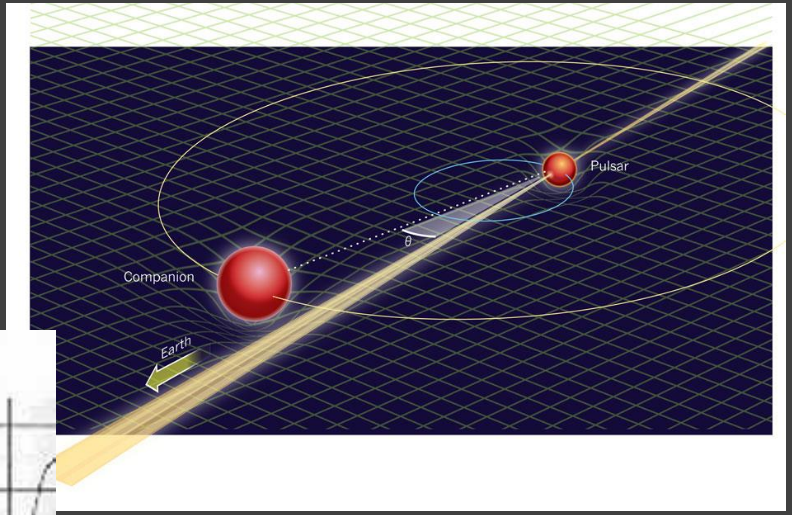
http://exoplanets.org/plots

Timing

Observations of a periodic process
(radio pulsar, binary system, pulsating star)
allows to identify a perturber





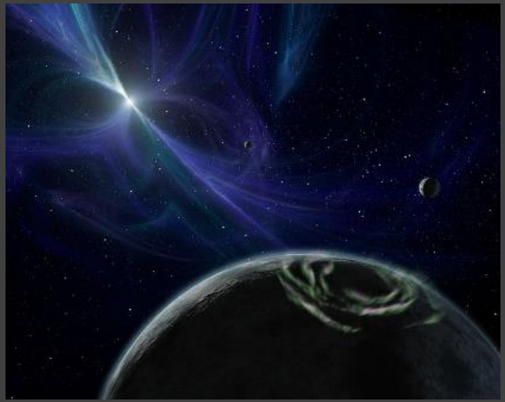


Planets around a radio pulsar

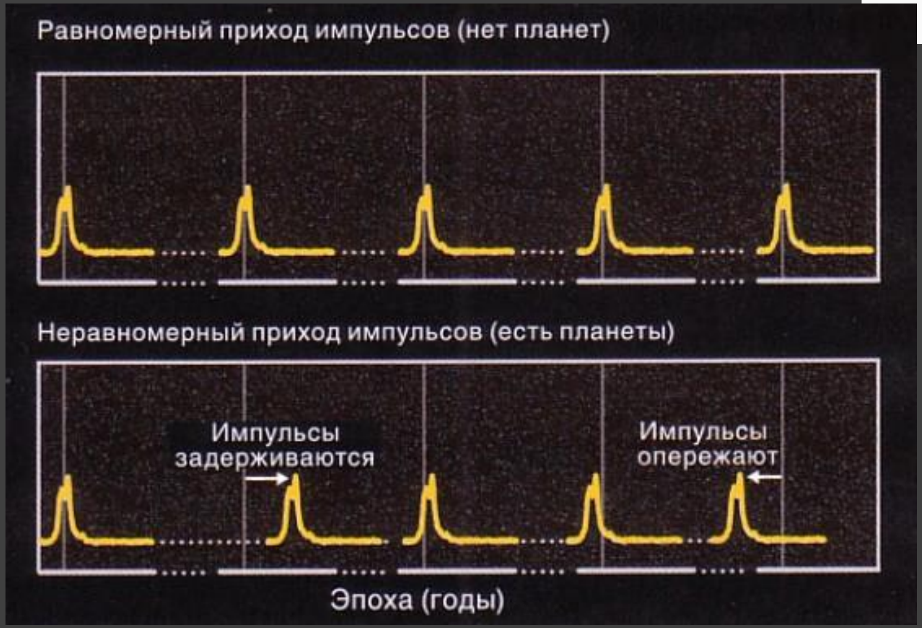
Wolszczan, Frail 1992

Three light planets

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)
A (b)	$0.020 \pm 0.002\ M_{\oplus}$	0.19	25.262 ± 0.003
B (c)	$4.3 \pm 0.2\ M_{\oplus}$	0.36	66.5419 ± 0.0001
C (d)	$3.9 \pm 0.2\ M_{\oplus}$	0.46	98.2114 ± 0.0002

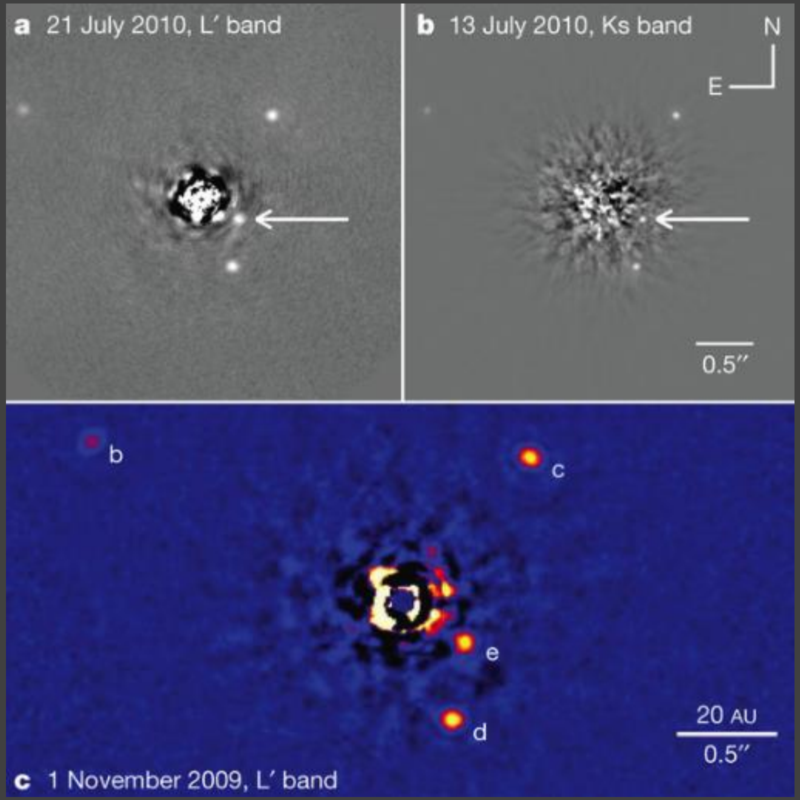


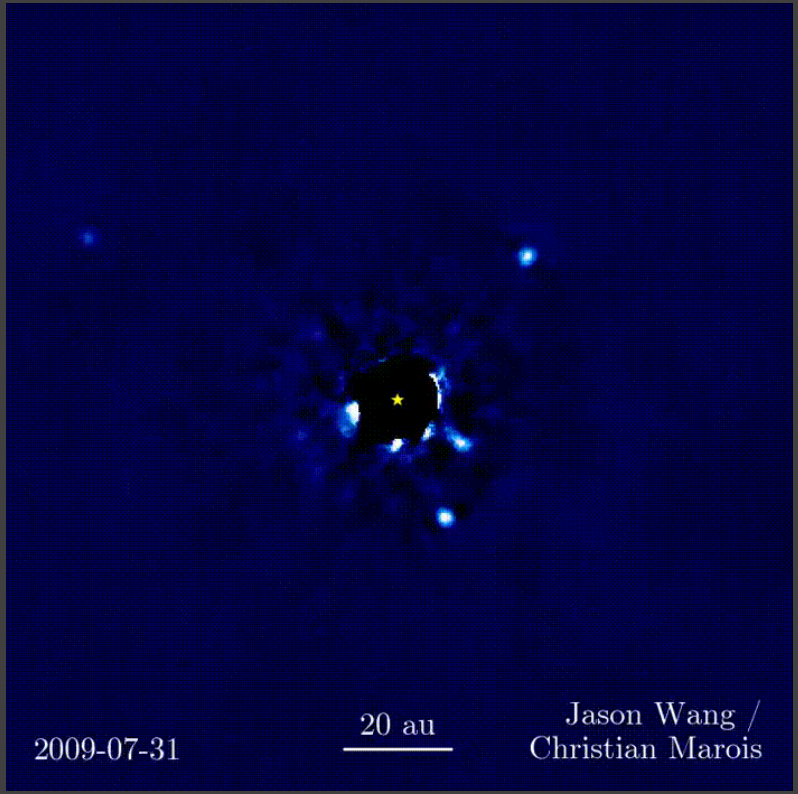
PSR B1257+12
Millisecond pulsar



Direct imaging

Now it is possible to see self-luminous planets (10^{-5} in flux) at >~1 arcsec.
For comparison: Solar system analogue at 10 pc gives for Jupiter 10^{-9} in flux and 0.5 arcsec.





Telescope properties

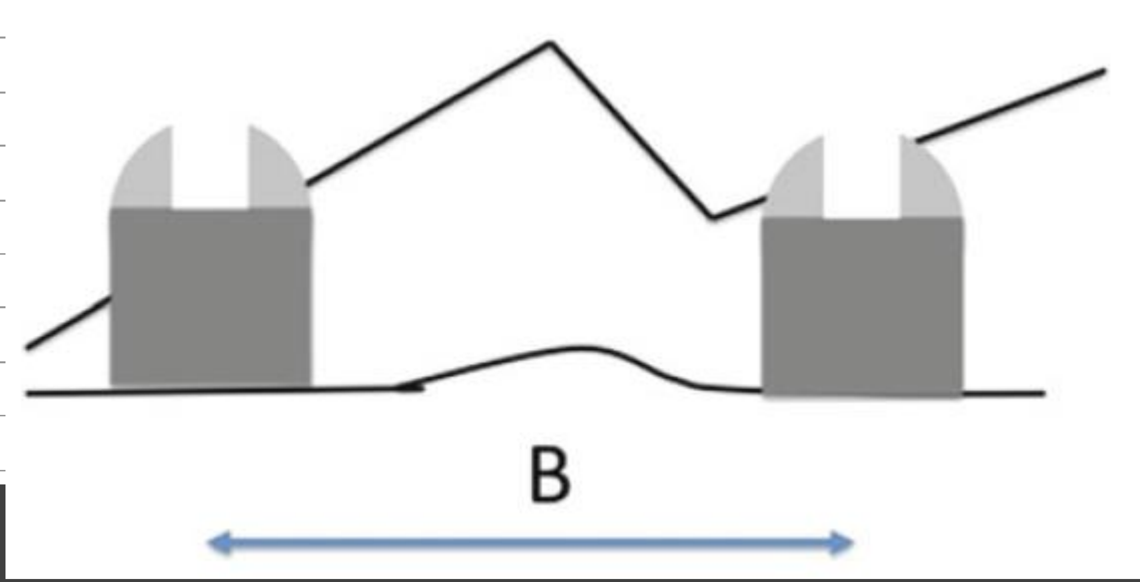
Instrument	Telescope	Wavelength (μm)	Ang. resol. (mas)	Coronagraph
ACS	HST	0.2–1.1	20–100	Lyot
STIS	HST	0.2–0.8	20–60	Lyot
NAOS–CONICA	VLT	1.1–3.5	30–90	Lyot/FQPM
VISIR	VLT	8.5–20	200–500	–
SINFONI–SPIFFI	VLT	1.1–2.45	28–62	–
SPHERE	VLT	0.95–2.32	24–62	Lyot/APLC/FQPM
PUEO	CFHT	0.75–2.5	4–140	Lyot
CIAO	SUBARU	1.1–2.5	30–70	Lyot
OSIRIS	Keck I	1.0–2.4	20–100	–
AO–NIRC2	Keck II	0.9–5.0	20–100	Lyot
ALTAIR–NIRI	Gemini N.	1.1–2.5	30–70	Lyot
GPI	Gemini S.	0.9–2.4	24–62	Lyot/APLC
PALM-3000 PHARO	Hale 200″	1.1–2.5	60–140	Lyot/FQPM
PALM-3000 Project1640	Hale 200″	1.06–1.76	43–71	APLC
AO–IRCAL	Shane 120″	1.1–2.5	100–150	–

$\Theta=(a/d)(1+e) =$
$= 1 \text{ arcsec } (a/AU)(d/pc)^{-1} (1+e)$

Ground optical interferometers

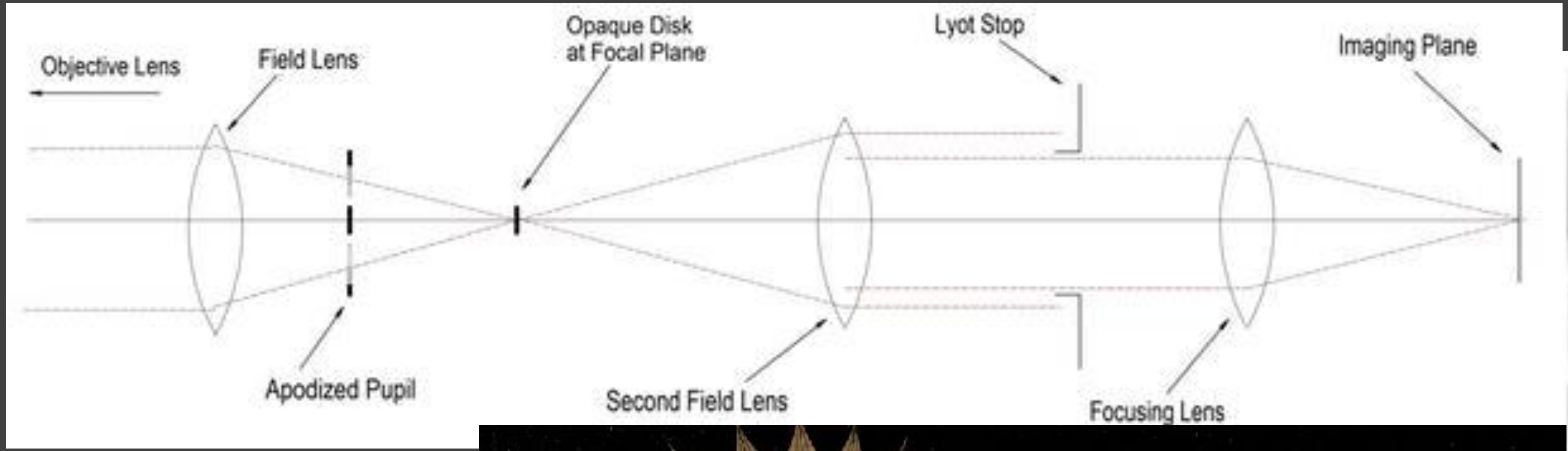
Instrument	Interf.	Baseline (m)	Bands	Ang. res. (mas)	Spec. res.	Aperture
AMBER	VLTI	16–200	J,H,K	0.6–14	35–15,000	3
MIDI	VLTI	16–200	N	4–80	20–220	2
PIONIER	VLTI	16–200	H,K	1.5–45	15	4
V2	Keck I	85	H,K,L	2–5	25–1800	2
Nuller	Keck I	85	N	10–16	40	2
Mask	Keck	1–10	J to L	13–400	None	2
Classic	CHARA	34–330	H,K	0.5–7	None	2
FLUOR	CHARA	34–330	K	0.7–7	None	2
MIRC	CHARA	34–330	J,H	0.4–5	40–400	4
BLINC	MMT	4	N	250	None	2
LMIRCAM	LBTI	14–23	L,M	27–72	None	2
NOMIC	LBTI	14–23	N	72–200	None	2

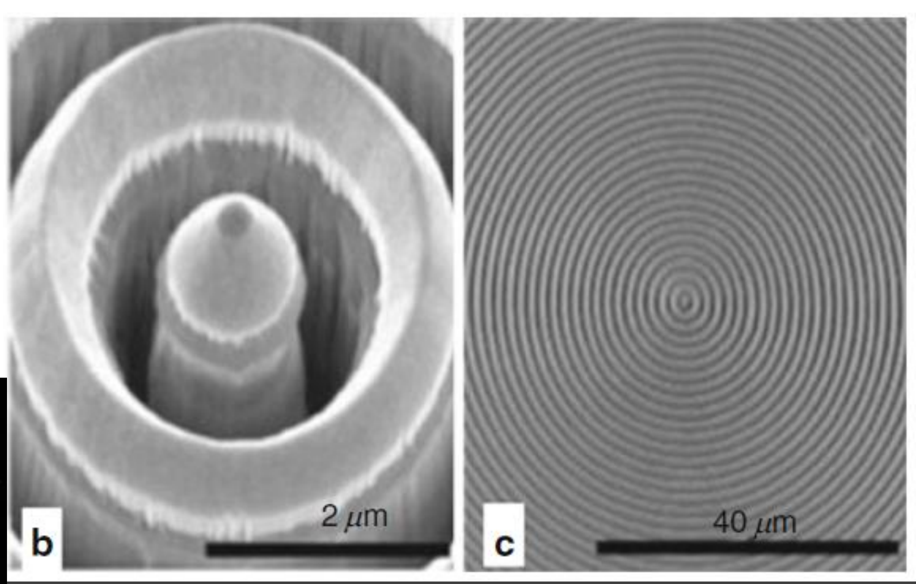
Better resolution,
but smaller aperture



Riccardo Claudi (in Bozza et al. 2016)

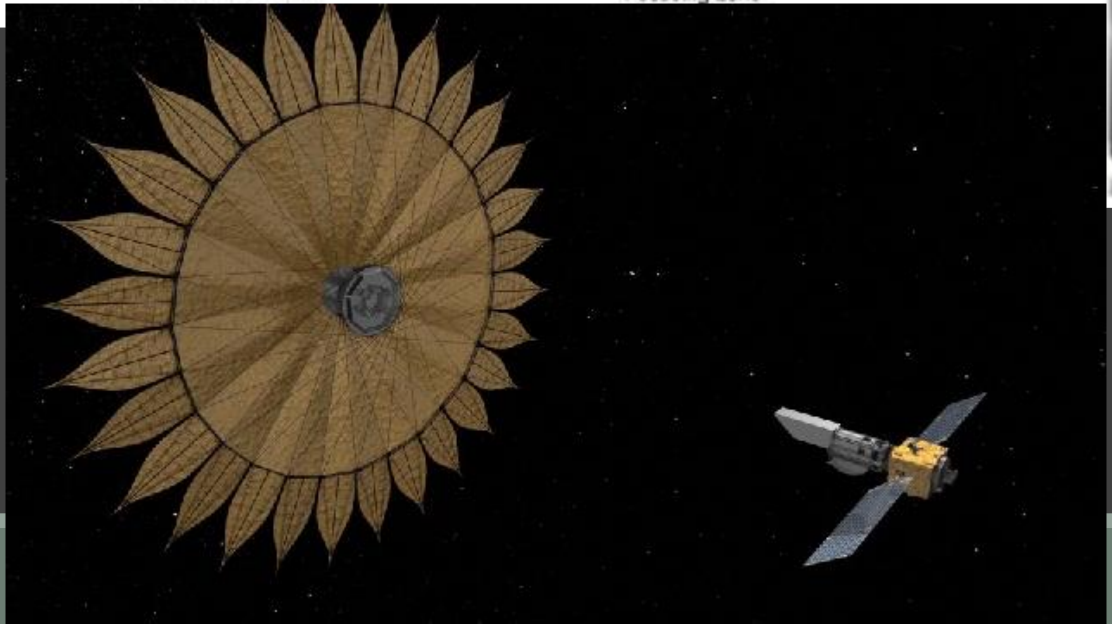
Coronagraphs



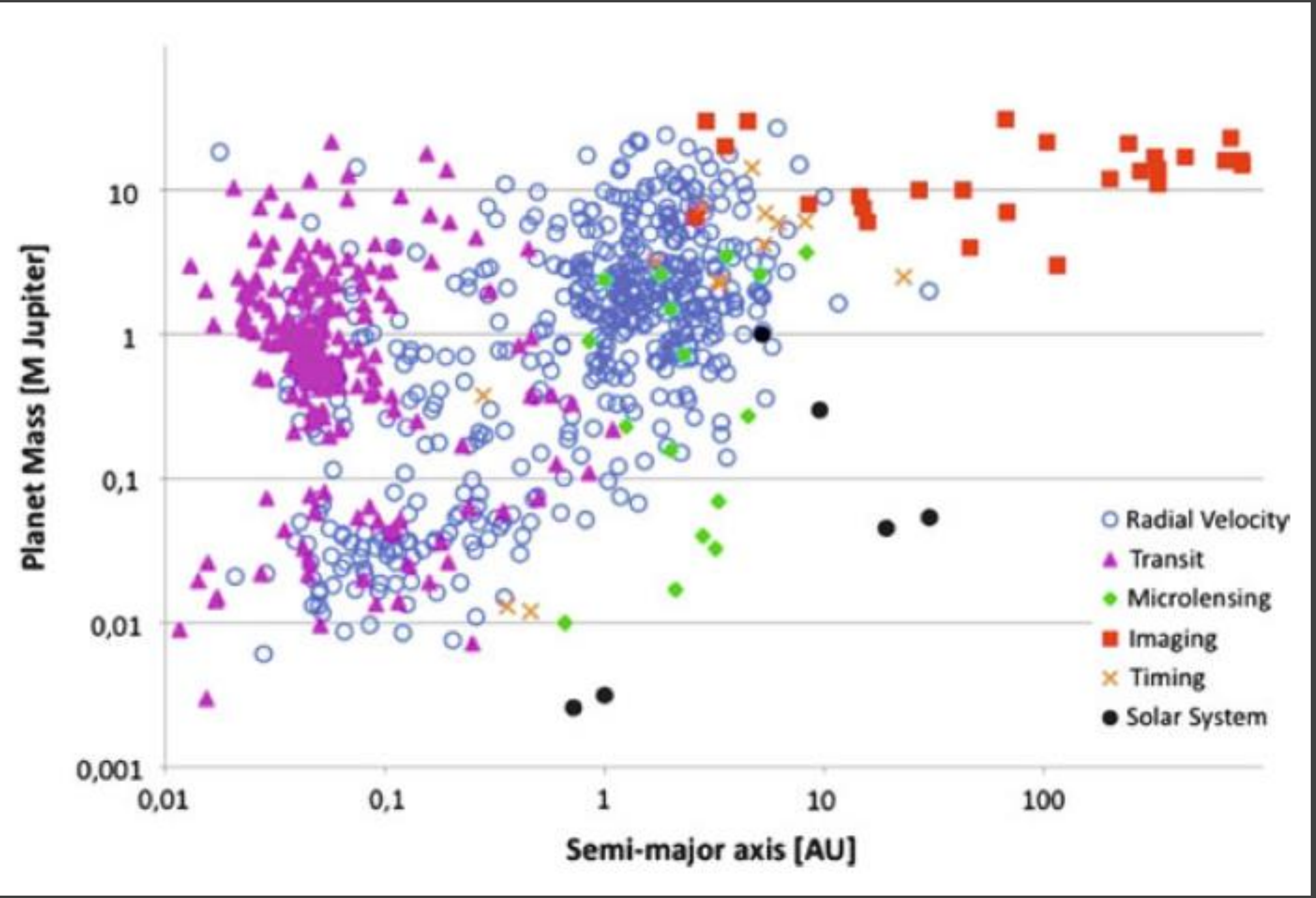


Riccardo Claudi (in Bozza et al. 2016)

To obtain planet images different kinds of coronagraphs are used.



Imaging vs. other methods

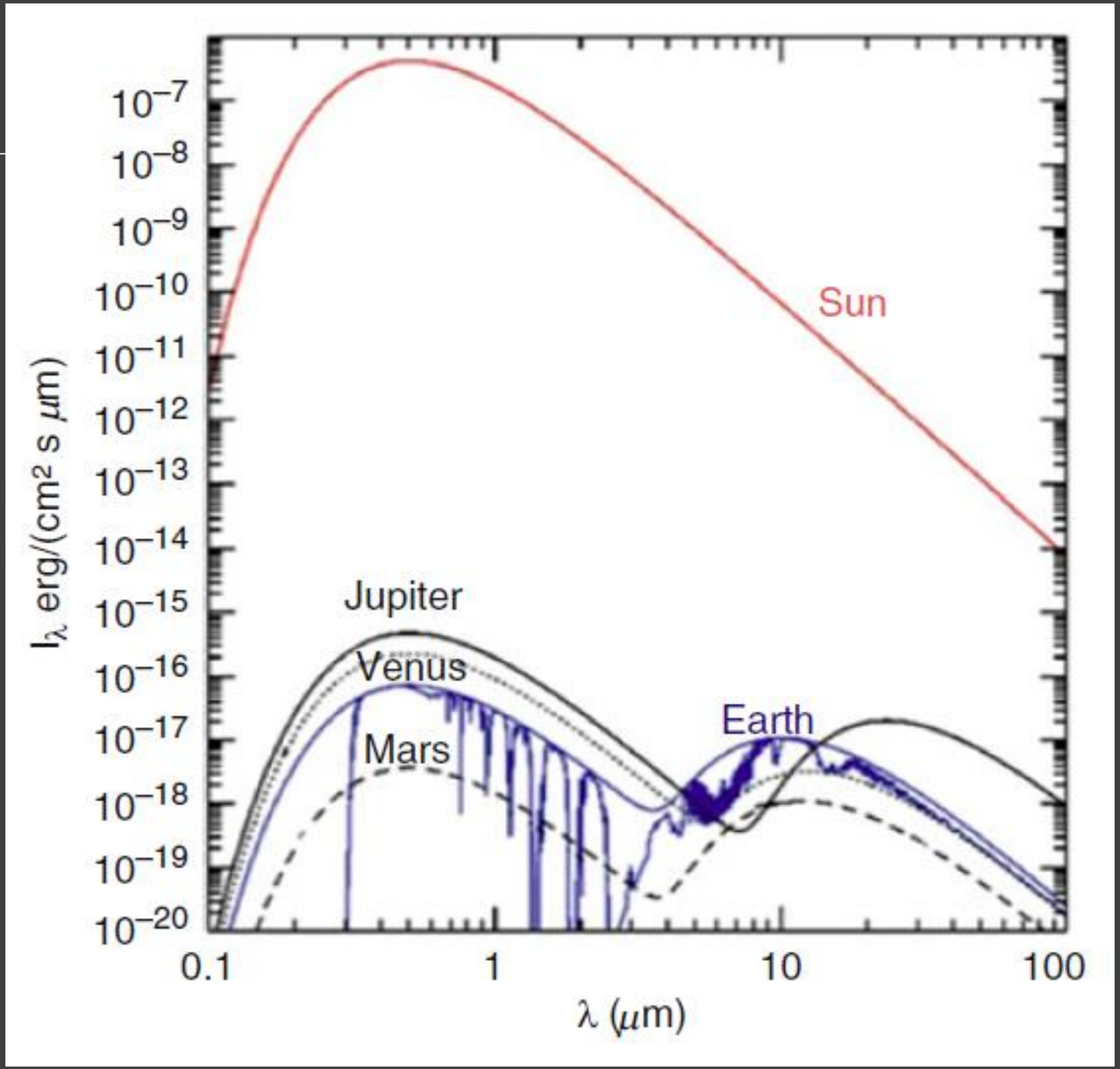


Riccardo Claudi (in Bozza et al. 2016)

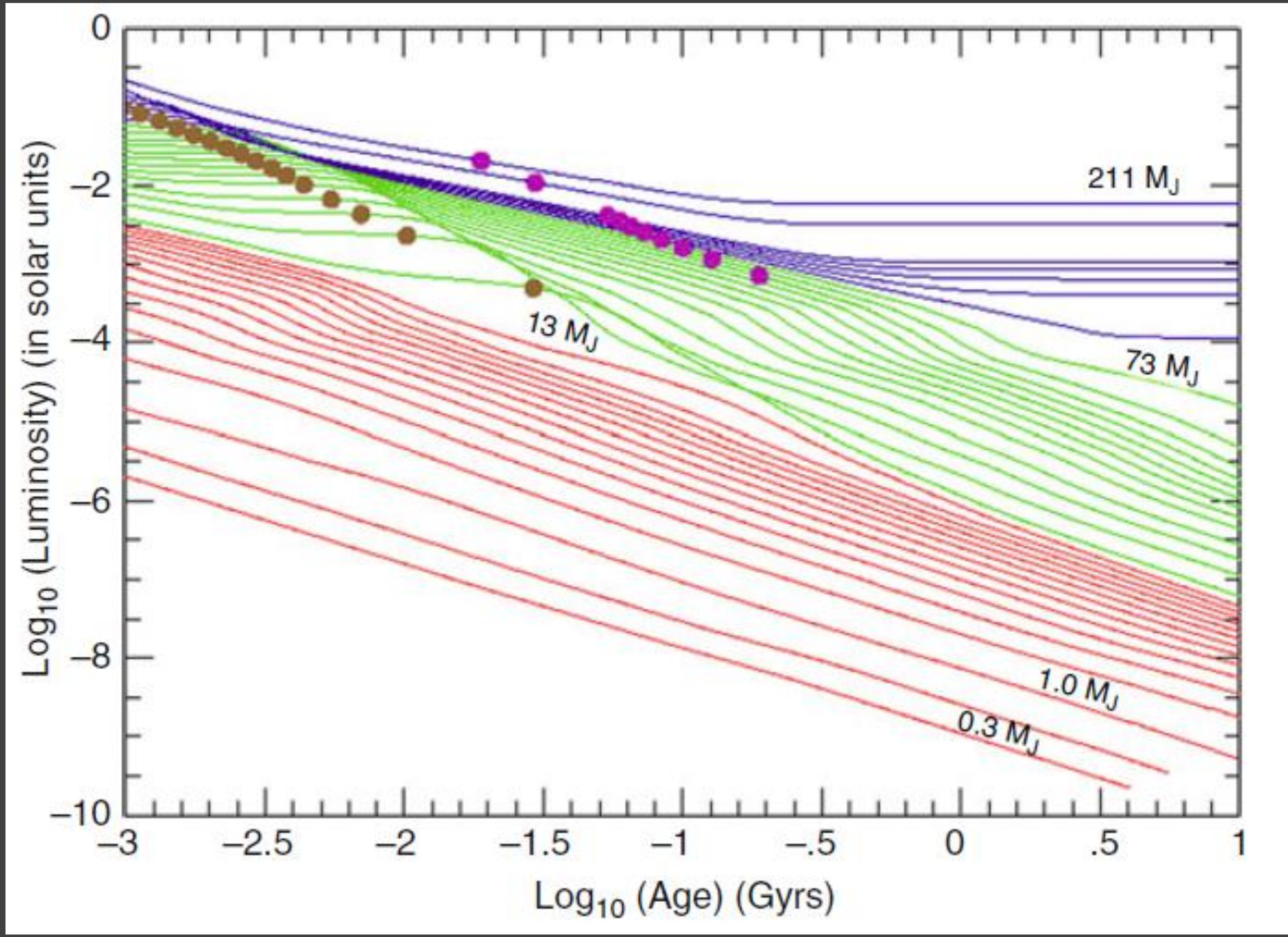
Solar system

Notice, how much better planets are visible in IR.
Especially Jupiter at 20-30 micrometers.

$$F_{\mathrm{p,Vis}} = A(\lambda, t)\phi(t)\frac{R_{\mathrm{p}}^2}{4a^2}B(\lambda, T_{\mathrm{eff}})R_{\star}^2,$$

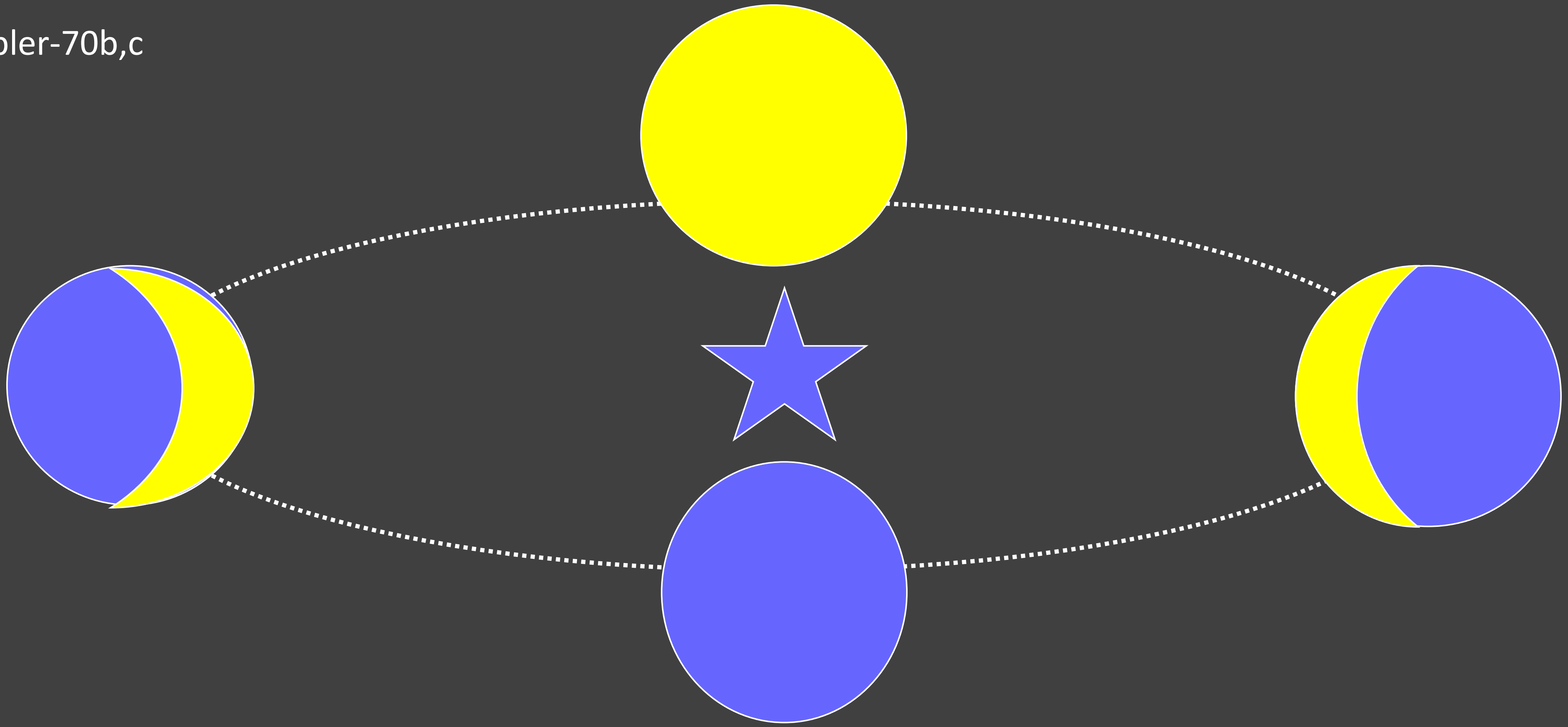


Young planets are hotter

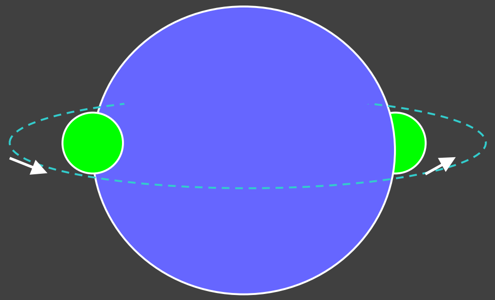


Planet light identification

Kepler-70b,c



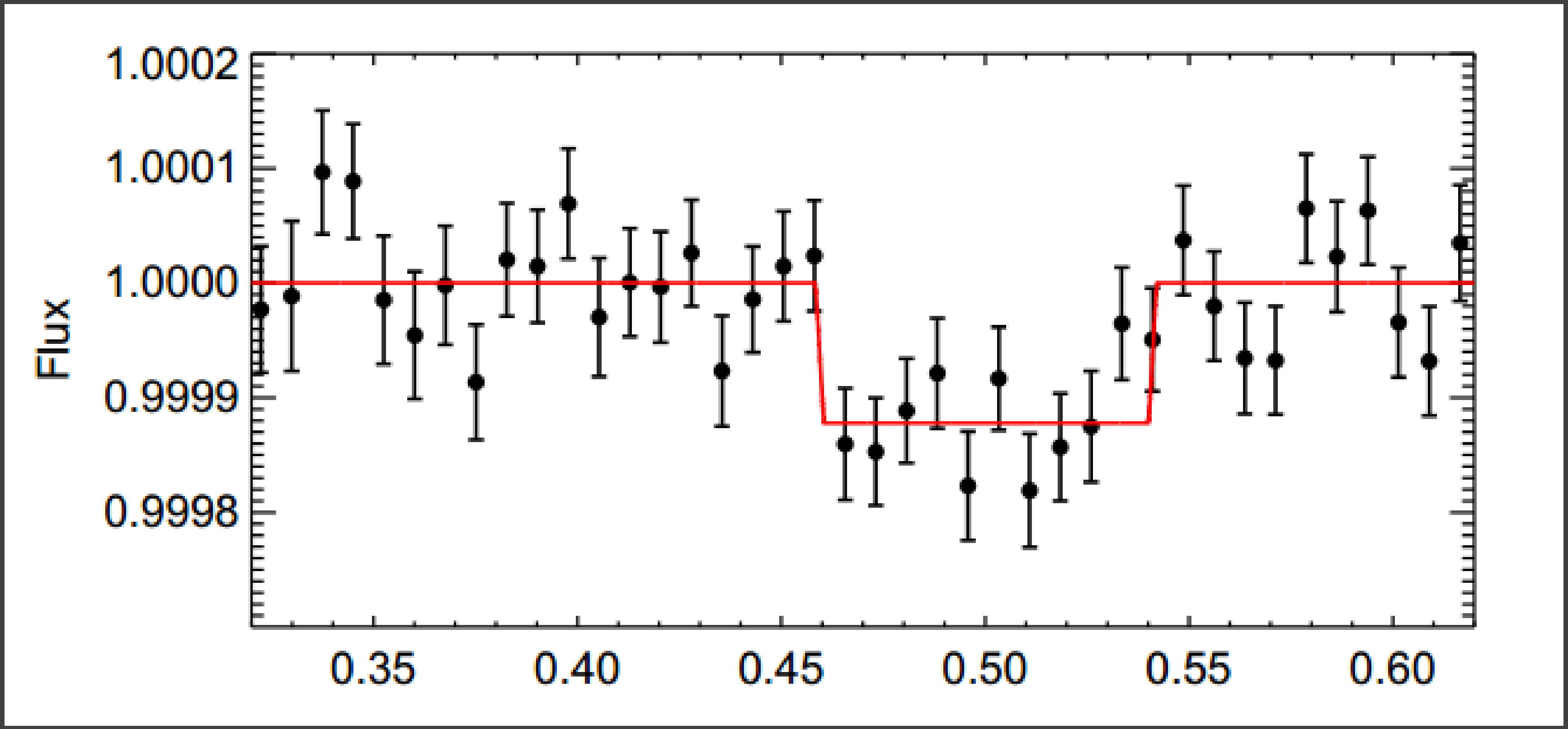
IR light



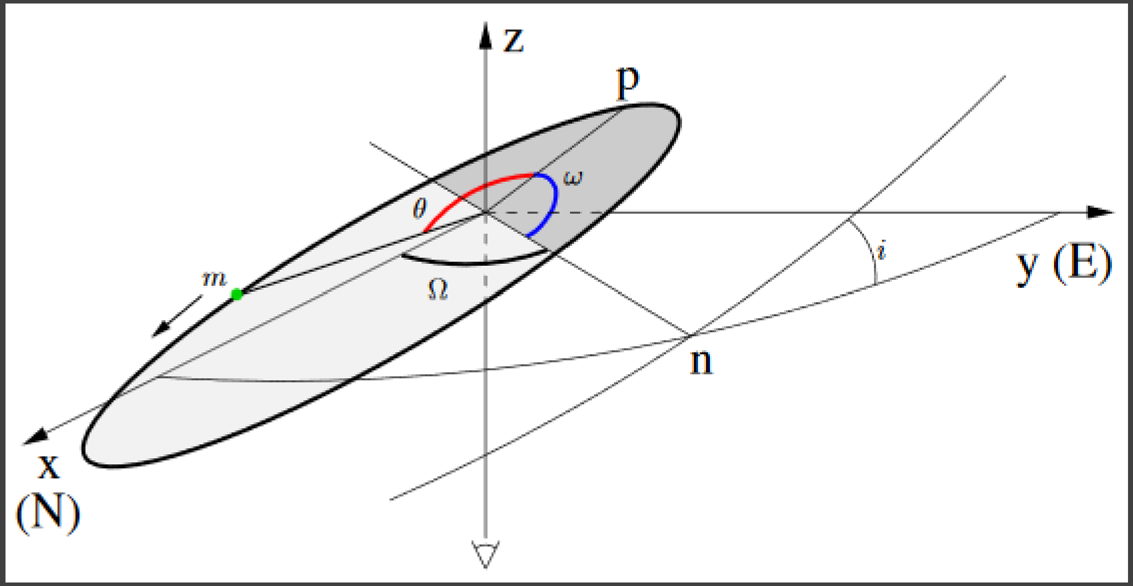
55 Cnc e
Mass: 7-8 Earth mass
Semi-major axis: 0.016 AU
Orbital period: 0.74 days

Temperature 2000-2600K

Occultation light curve



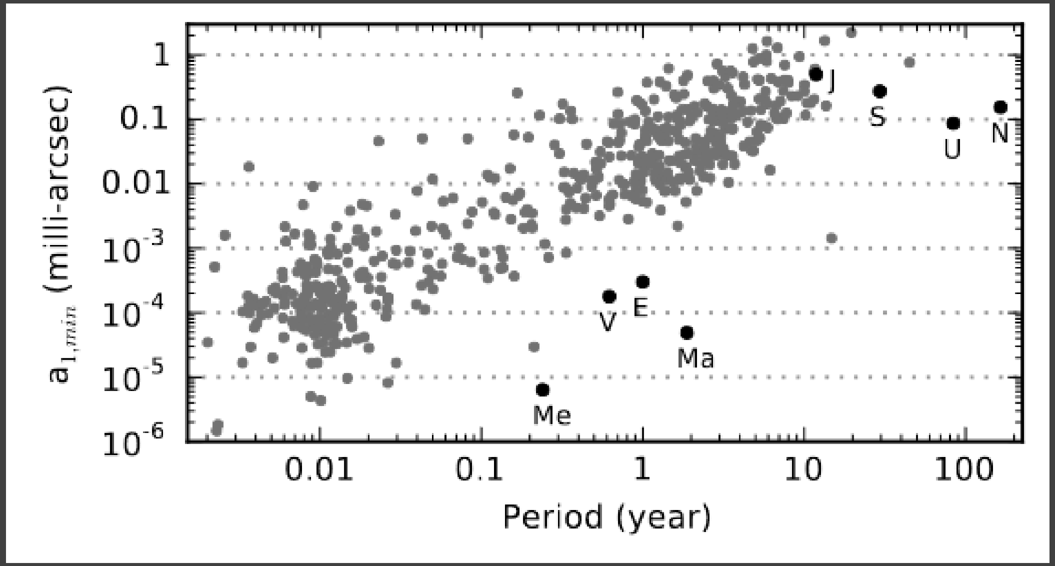
Astrometric detection



$$4\pi^2 \frac{\bar{a}_1^3}{P^2} = G \frac{M_P^3}{(M_* + M_P)^2},$$

It is easier to detect massive long period planets on eccentric orbits.

Astrometry allows to determine $M^3_{planet}/(M_{star}+M_{planet})^2$



Data on 570 stars with planets are shown.
Solar system data is scaled for a star at 10 pc.

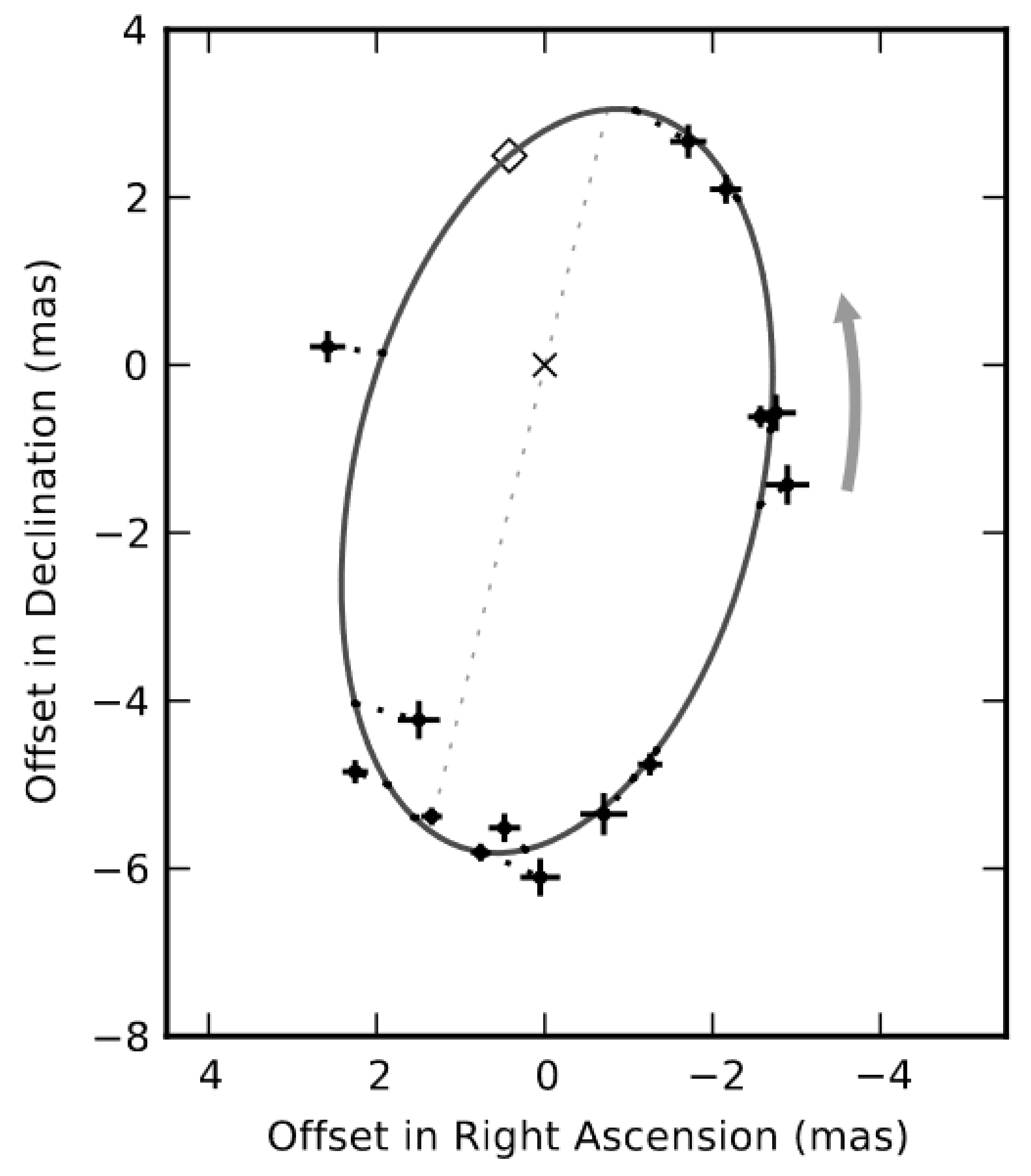
1505.06869

The only candidate

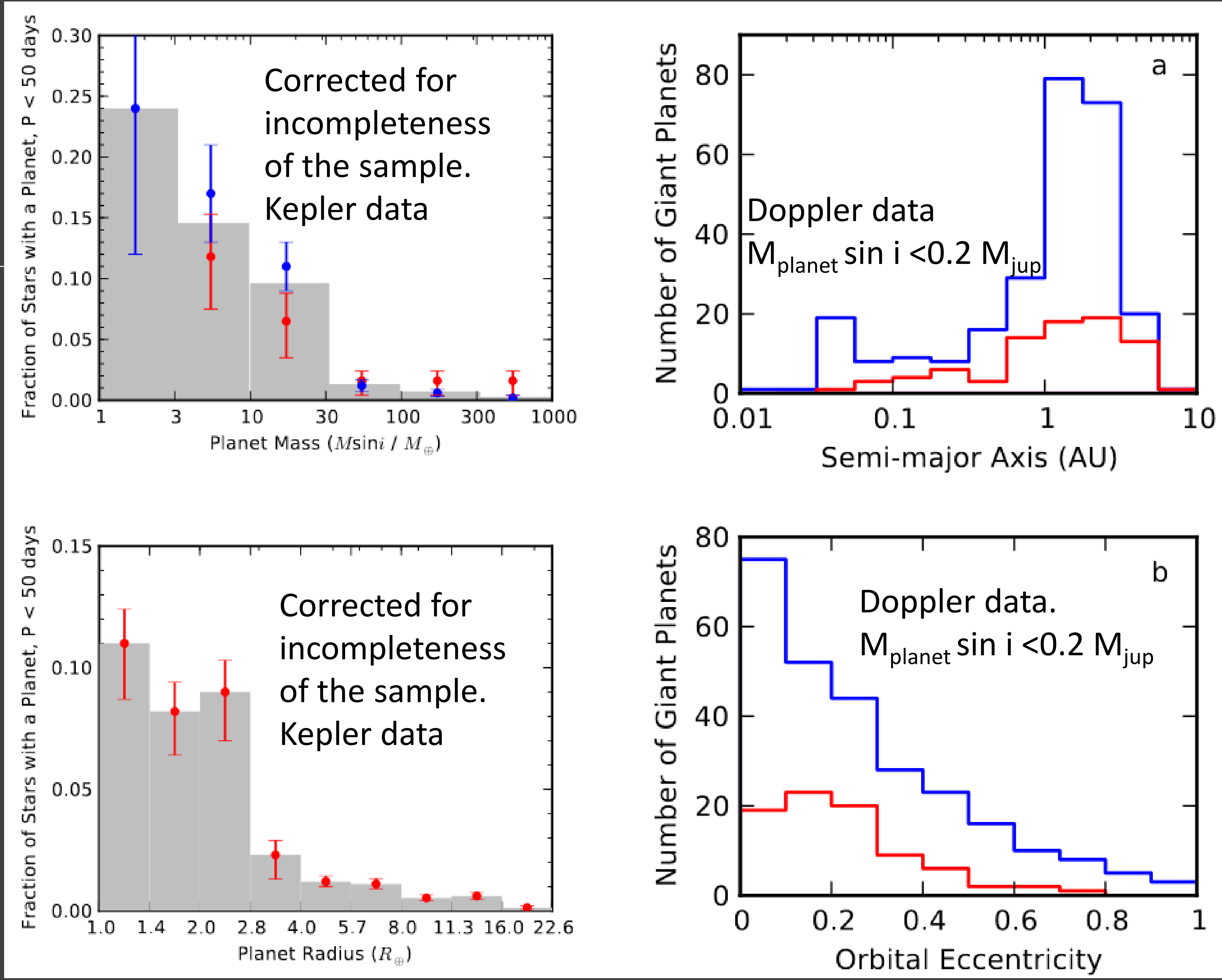
Came out to be a brown dwarf with 28 M_{jup}.

Now waiting for Gaia data.

Fig. 15.— The barycentric orbit of the L1.5 dwarf DENIS-P J082303.1-491201 caused by a 28 Jupiter mass companion in a 246 day orbit discovered through ground-based astrometry with an optical camera on an 8 m telescope (*Sahlmann et al.*, 2013a).

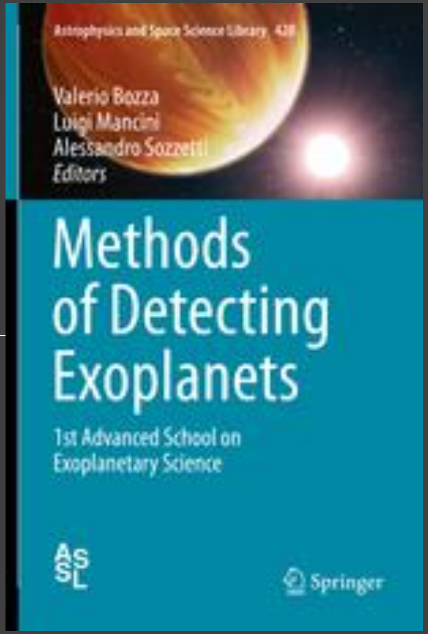


Planetary statistics



1505.06869

Literature



arxiv:1505.06869 Exoplanet Detection Techniques
arxiv:1504.04017 The Next Great Exoplanet Hunt
arxiv:1410.4199 The Occurrence and Architecture of Exoplanetary Systems

arXiv:1708.00896 Timing by Stellar Pulsations as an Exoplanet Discovery Method
arxiv:1706.09849 Transit Timing and Duration Variations for the Discovery and Characterization of Exoplanets
arxiv:1705.05791 Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life
arxiv:1704.07832 Mapping Exoplanets
arxiv:1701.05205 Characterizing Exoplanets for Habitability
arxiv:1411.1173 Astrometric exoplanet detection with Gaia
arxiv:1001.2010 Transits and Occultations
arxiv:0904.0965 Astrometric detection of earthlike planets
arXiv:0904.1100 Exoplanet search with astrometry
arxiv:0902.1761 Detection of extrasolar planets by gravitational microlensing